Starburst Galaxies as possible sources of UHECRs and neutrinos

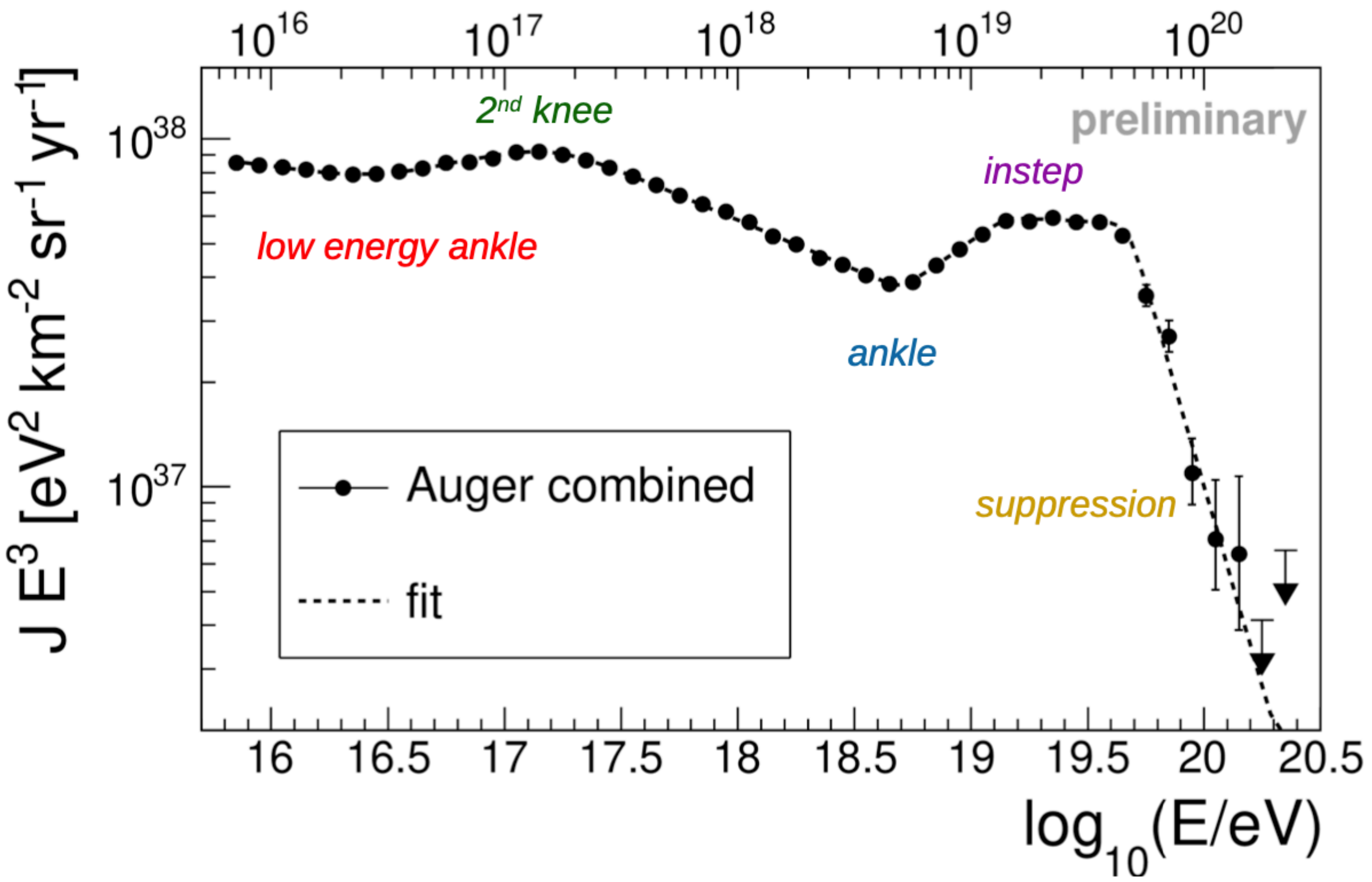
A. Condorelli, D. Boncioli,
E. Peretti, S.Petrera

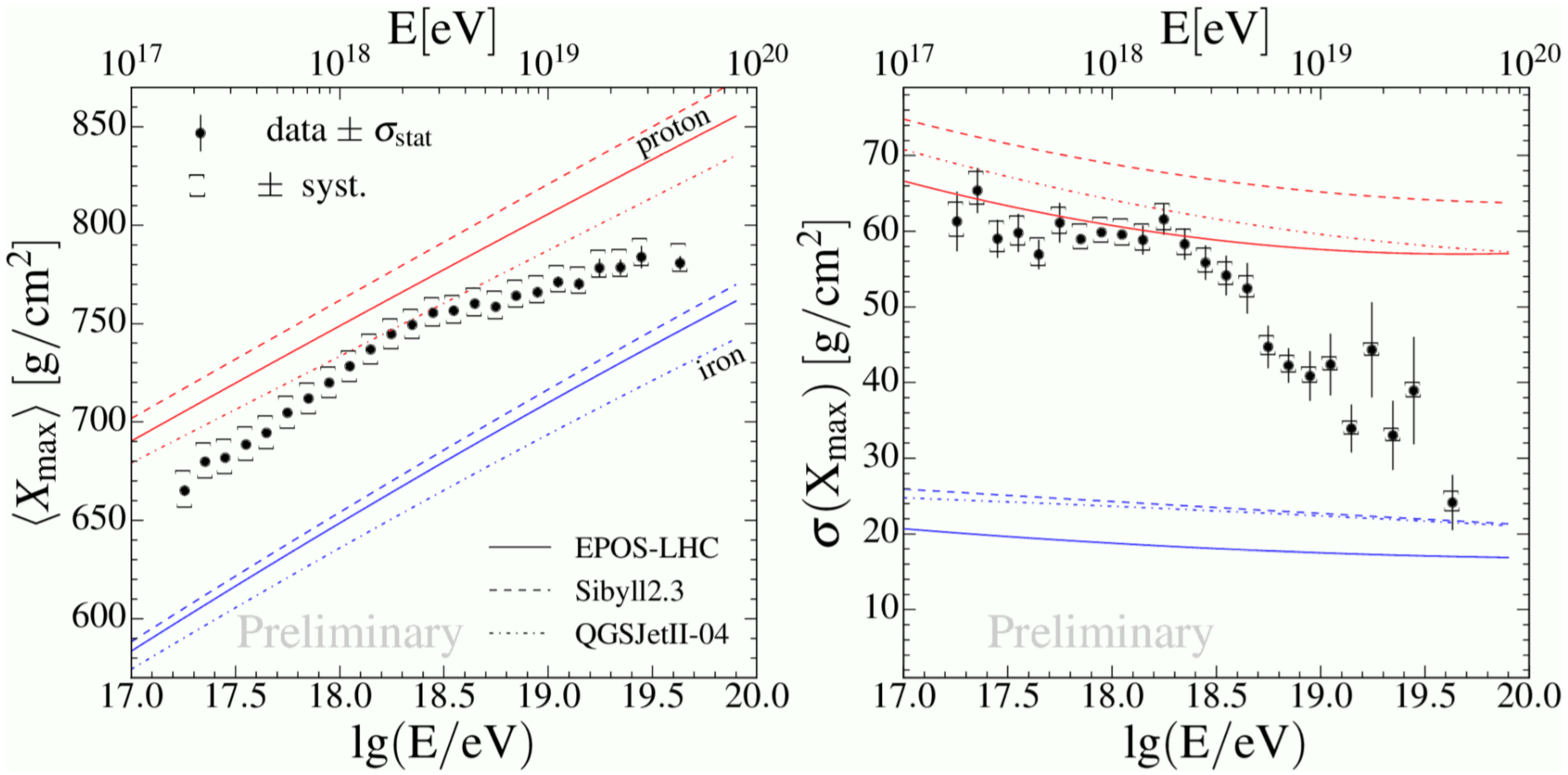
Paris Saclay AstroParticle Symposium, 26/10/2021

Outline

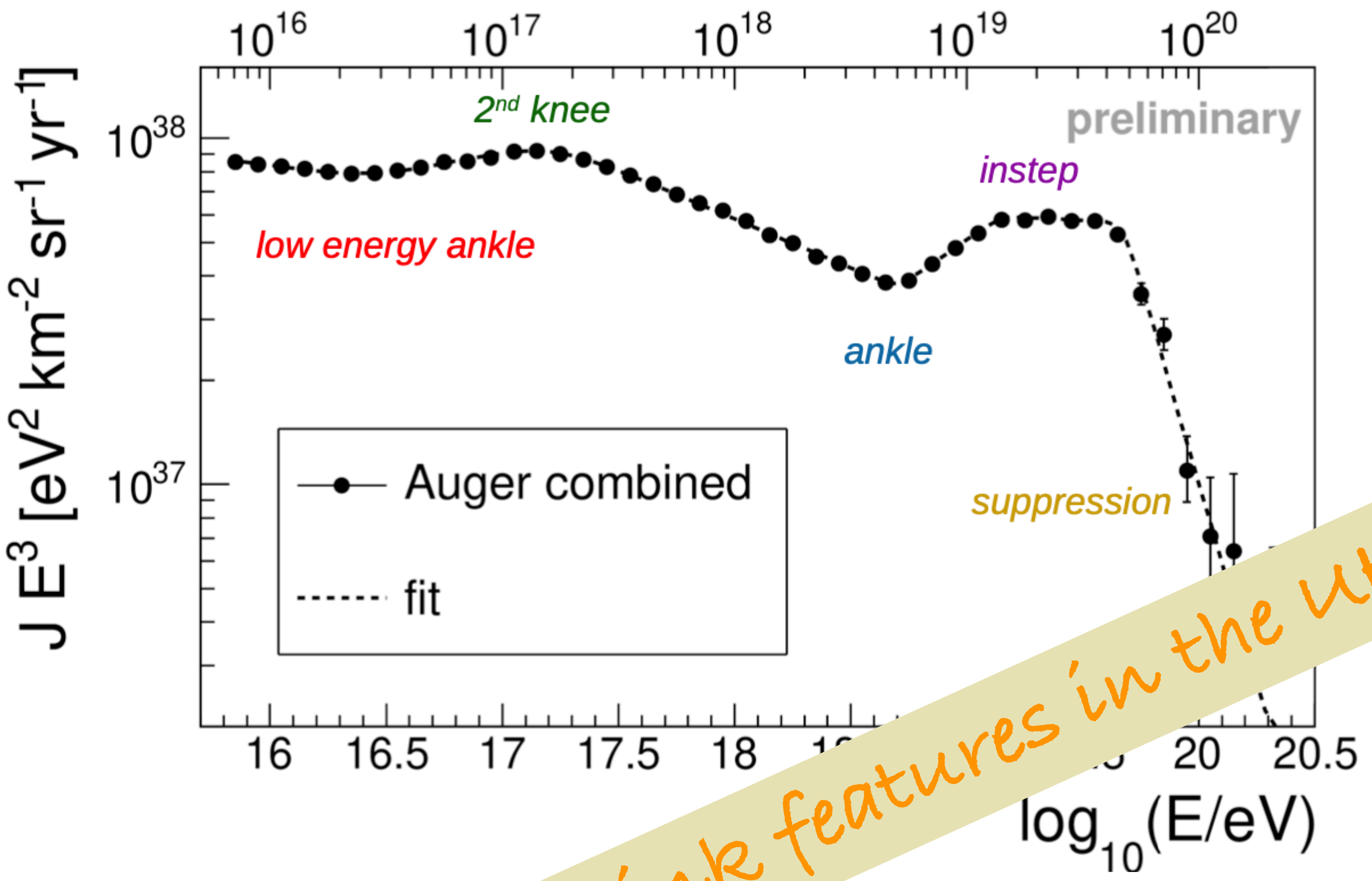
- ✳Motivation: astrophysical interpretation of the Pierre Auger data
- ✳Source-propagation model
- ✳Application to Starburst Galaxies
- ✳Analysis & results
- ✳Conclusions and future perspectives

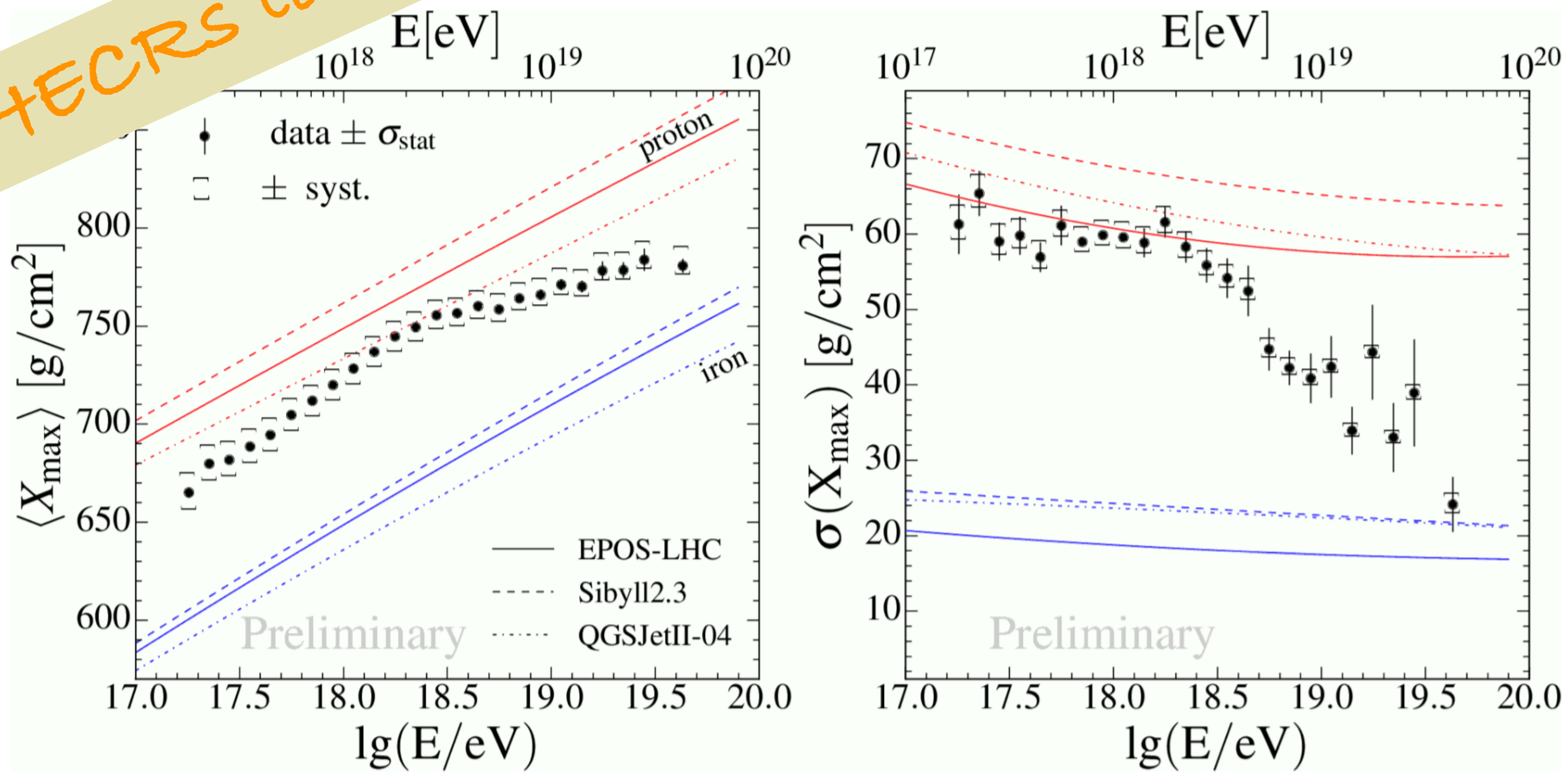
Energy spectrum and mass composition by PAO





Energy spectrum and mass composition by PAO





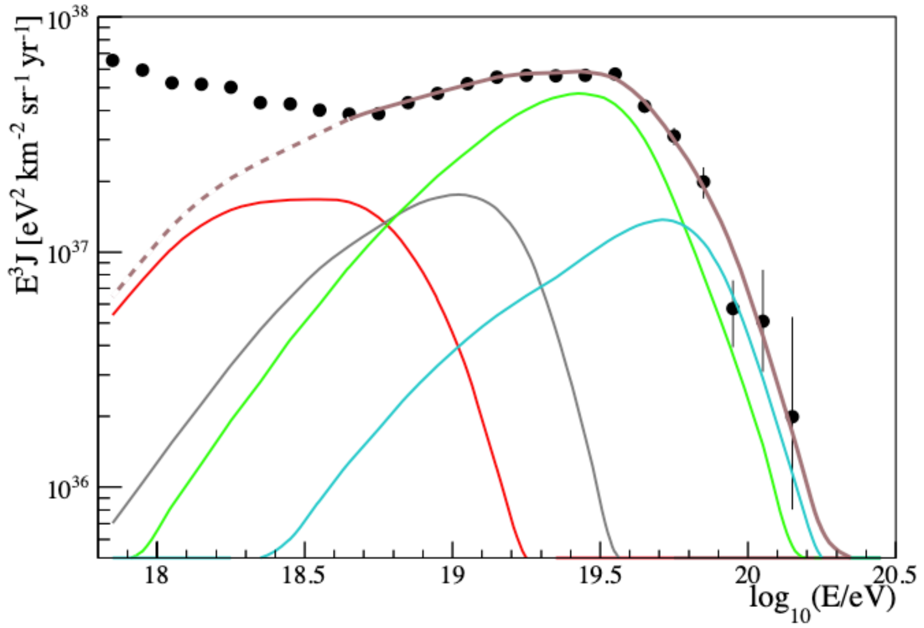
It is possible to link features in the UHECRs to astrophysical processes?

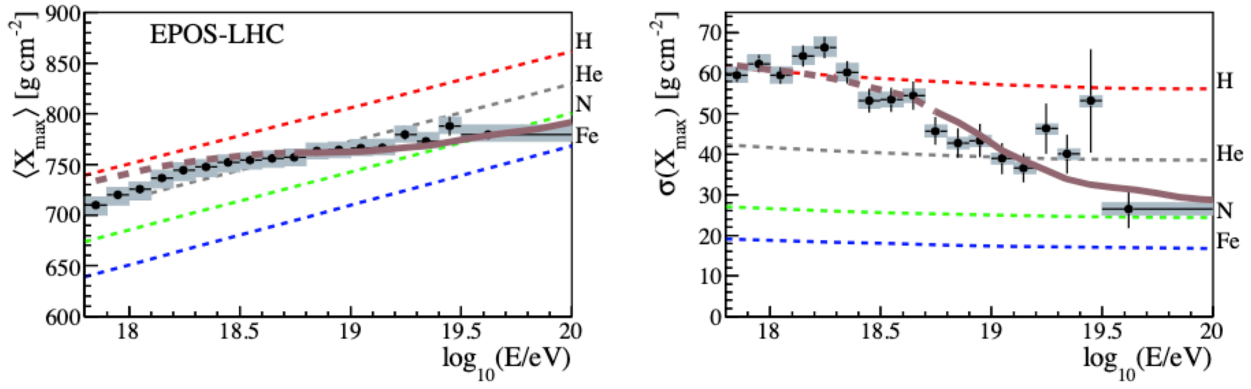
Astrophysical interpretation of Auger data

Fitting both the spectrum and composition, one can infer information about the source scenarios which are compatible to data.

Combined fit

See also: Sullivan's talk

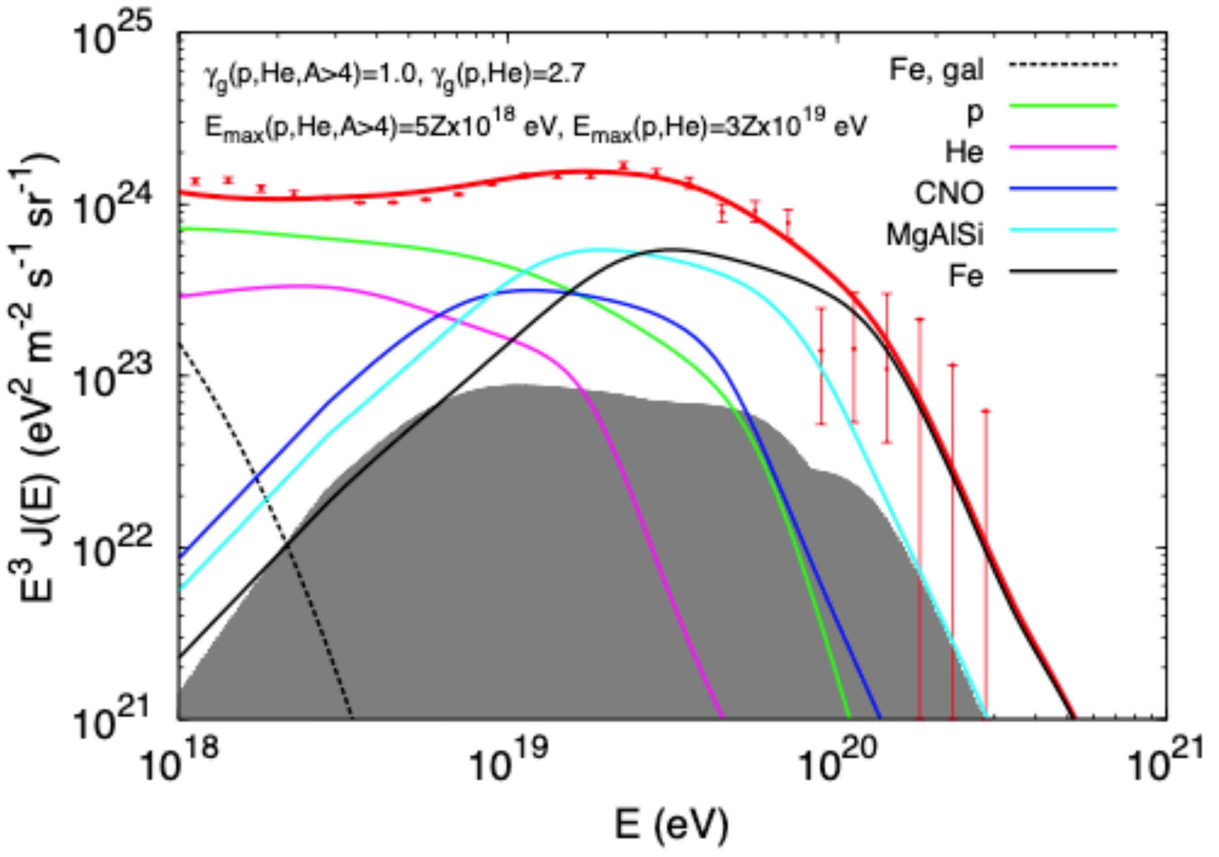


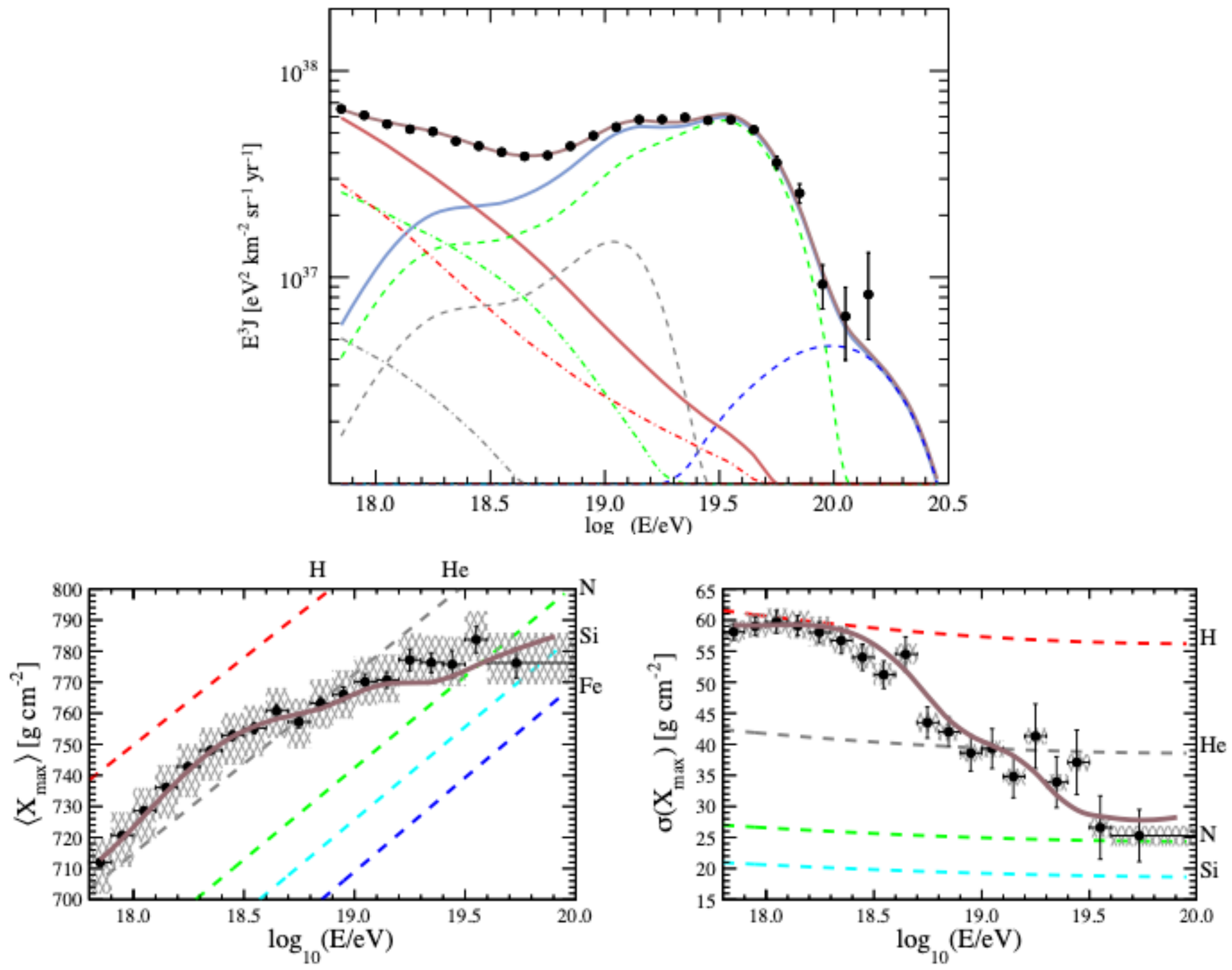


- ✳ Nuclei are accelerated at the sources.
- ✳ A hard injection spectrum at the sources is required.
- ✳ Suppression due to photo-interactions and by limiting acceleration at the sources, while the ankle feature is not easy to accomodate.

Combined fit across the ankle

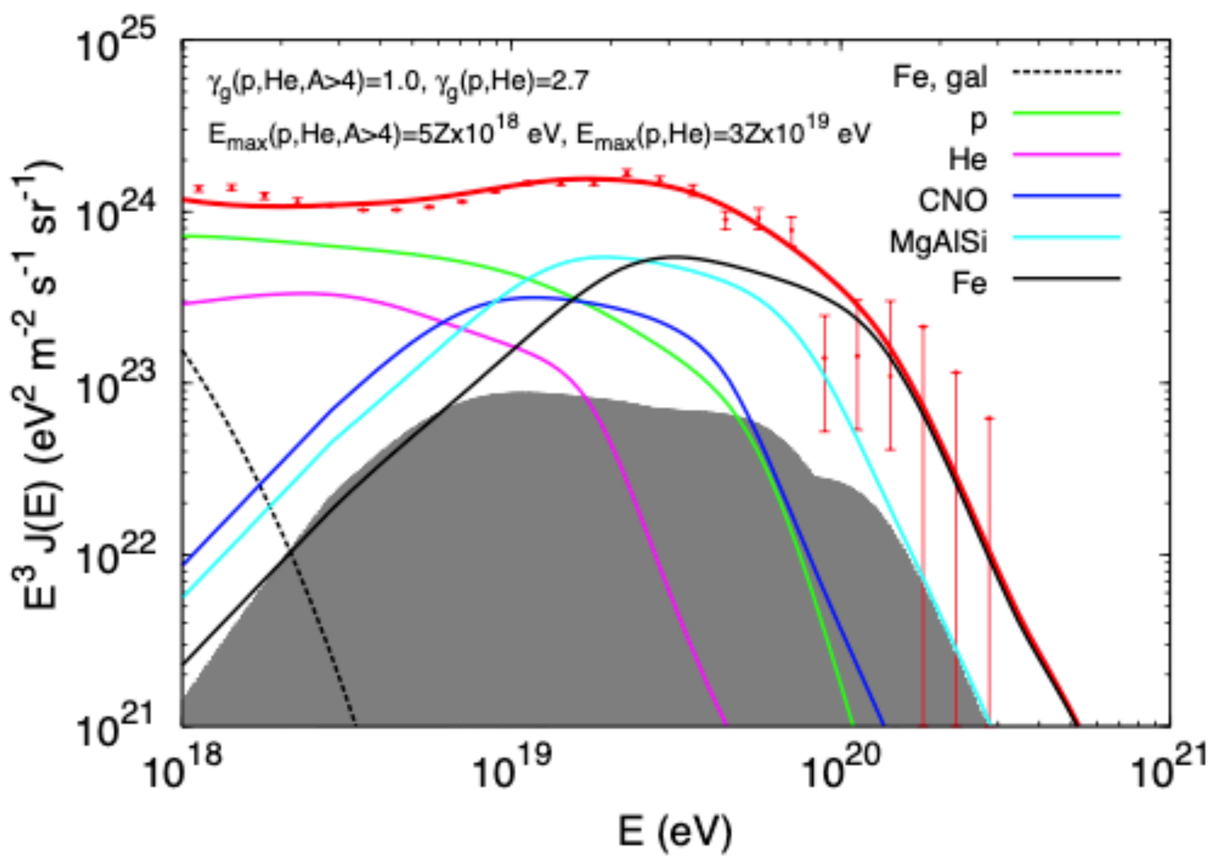
The ankle feature can be described as a superposition of two components.





Combined fit across the ankle

The ankle feature can be described as a superposition of two components.



- ✴Hard spectral index at high energies;
- ✴Soft spectral index at low energies.

Possible solutions:

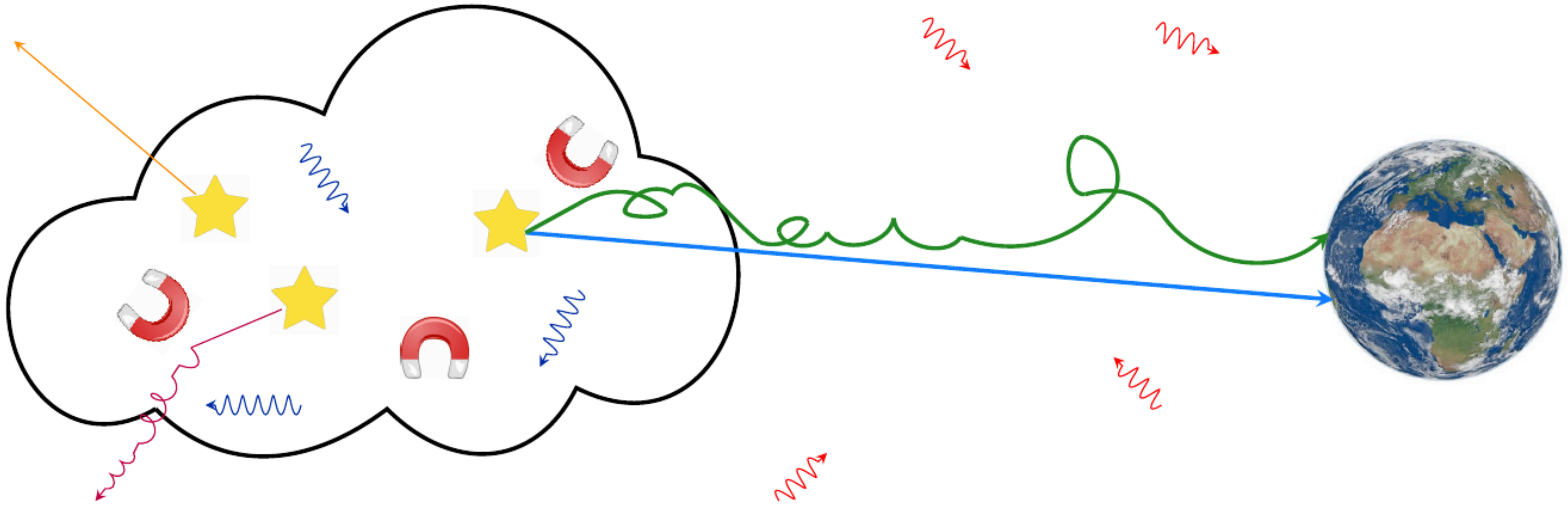
Different classes of sources

Interactions at the source

R. Aloisio, V. Berezinsky and P. Blasi, JCAP 10 (2014), 020

Source-propagation model

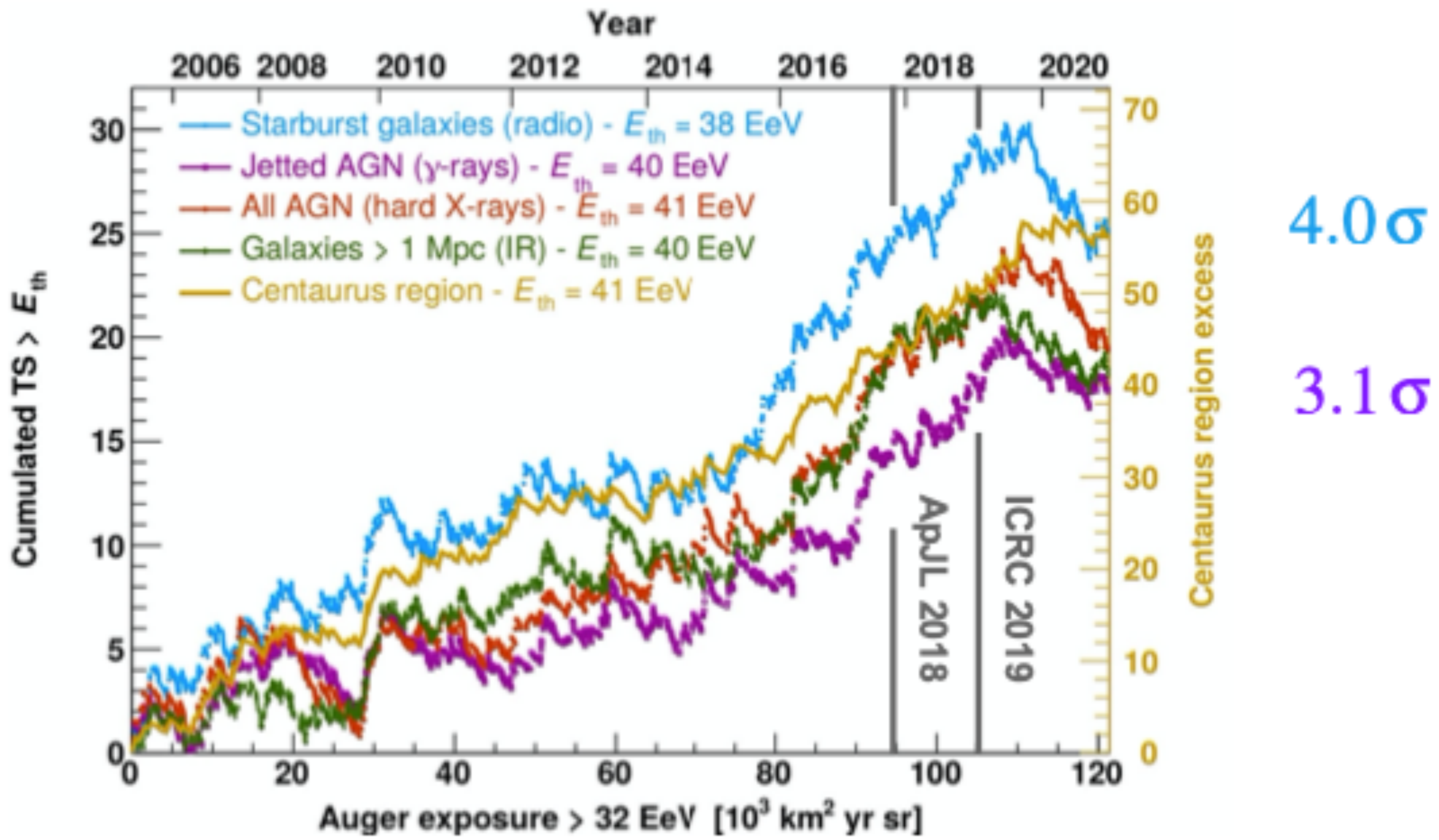
- Accelerated particles confined in the environment surrounding the source;
- Presence of photon and gas density;
- High energy particles–> escape with no interaction;
- Low energy particles –> Pile-up of nucleons at lower energies.



M. Unger, G.R. Farrar and L.A. Anchordoqui, Phys. Rev. D 92, 123001 (2015)

Application to Starburst Galaxies

- Motivation: Acceleration & Correlation.
- Benchmark model: M82.
- Leaky box model: computation of interaction and escape times.

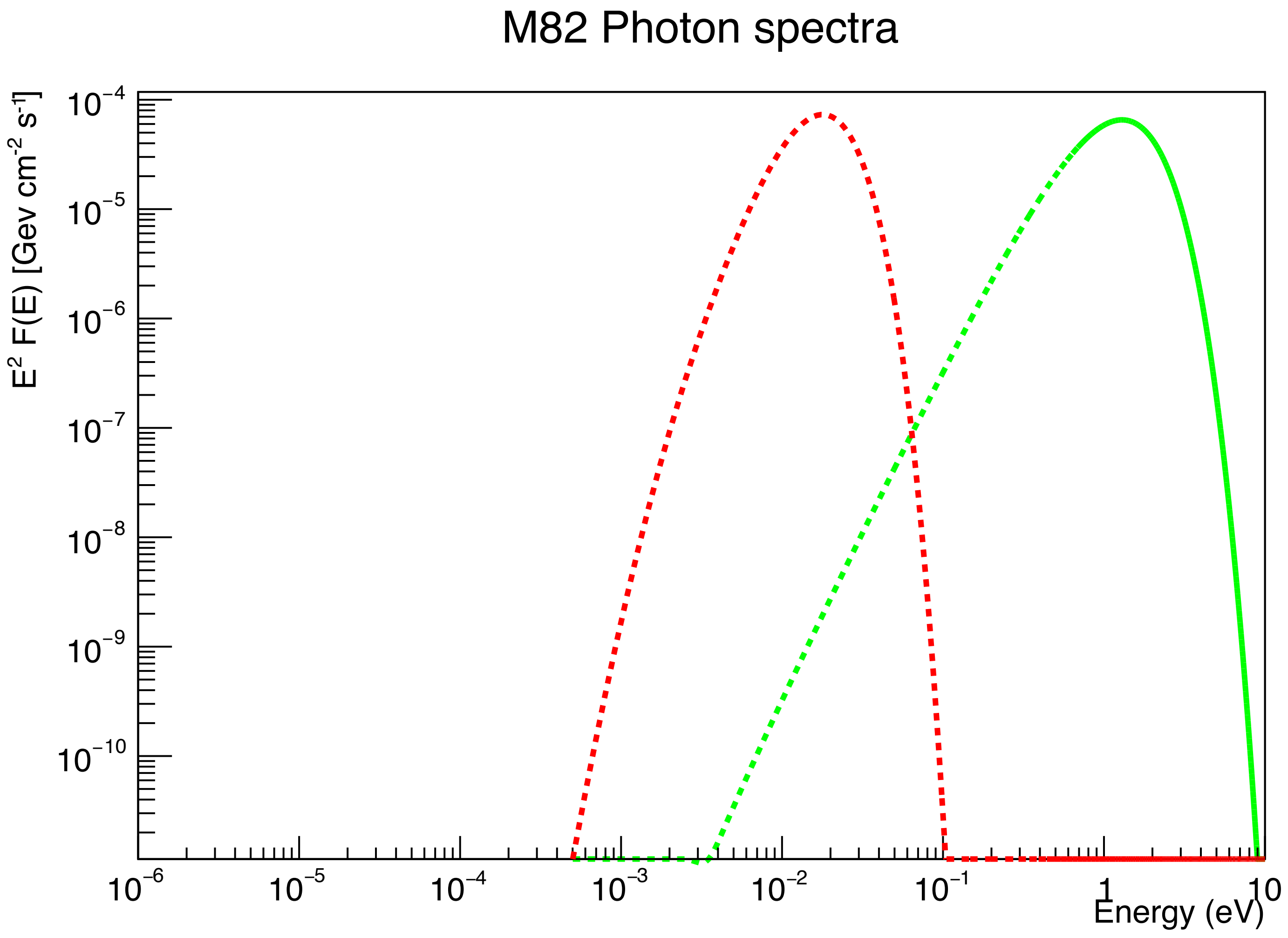


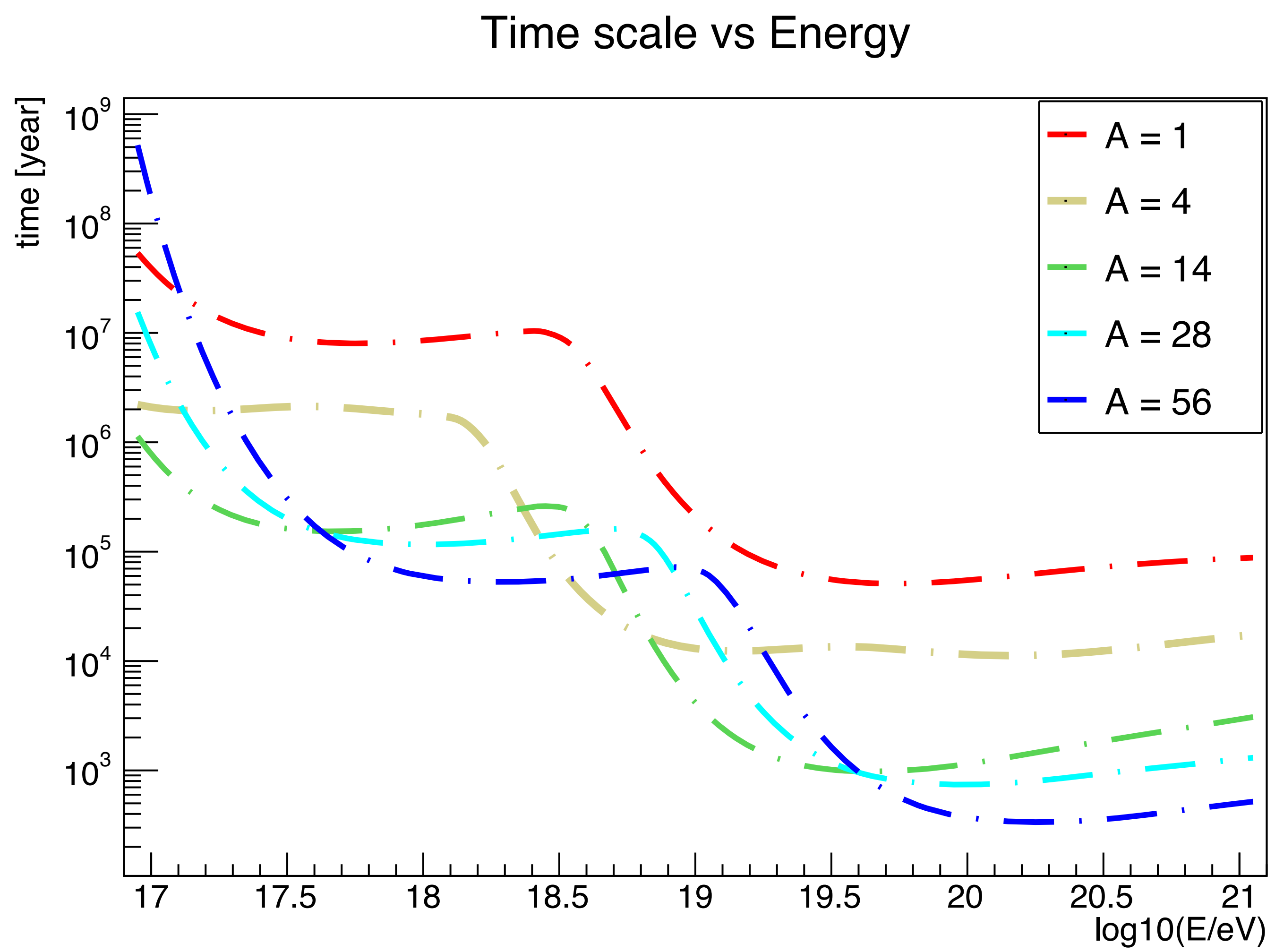
G. E. Romero, A. L. Müller and M. Roth, Astron. Astrophys. 616 (2018), A57
L. A. Anchordoqui, Phys. Rev. D **97** (2018) no.6, 063010

J. Biteau for the Pierre Auger Collaboration, ICRC2021

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

Photo-interaction time





$$\frac{1}{\tau} = \frac{1}{2\Gamma^2} \int_{\epsilon'_{\min}}^{2\Gamma\epsilon} \int_{\epsilon=0}^{+\infty} \frac{n_\gamma(\epsilon)}{\epsilon^2} \, \mathrm{d}\epsilon \, \sigma(\epsilon')\epsilon' \, \mathrm{d}\epsilon'$$

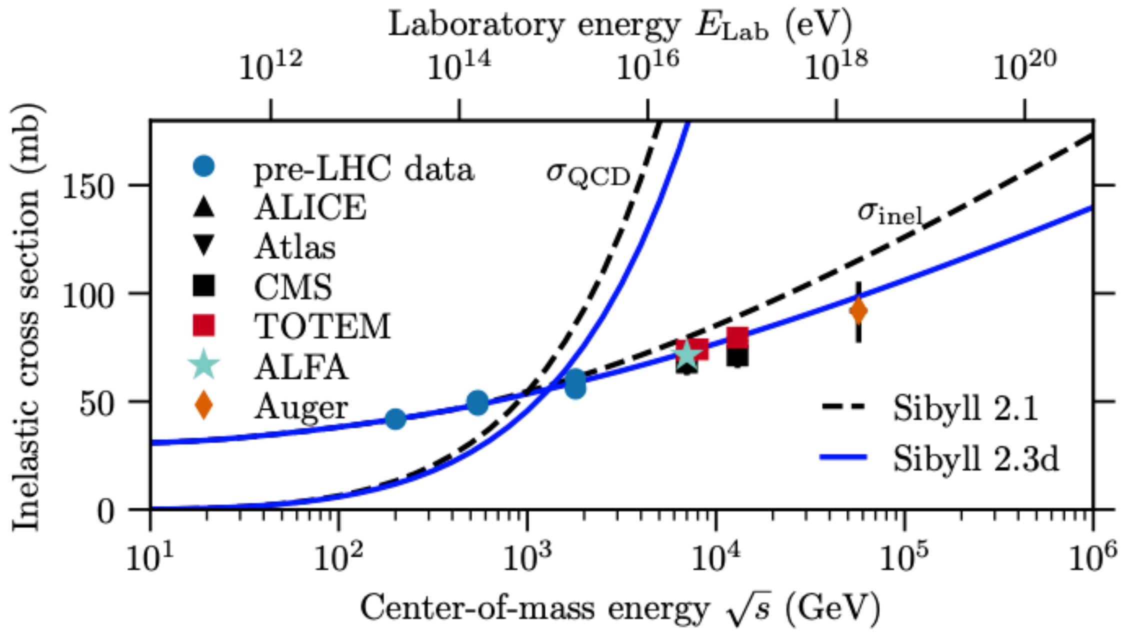
Adapting SimProp (software for UHECRs propagation in extra-galactic space):

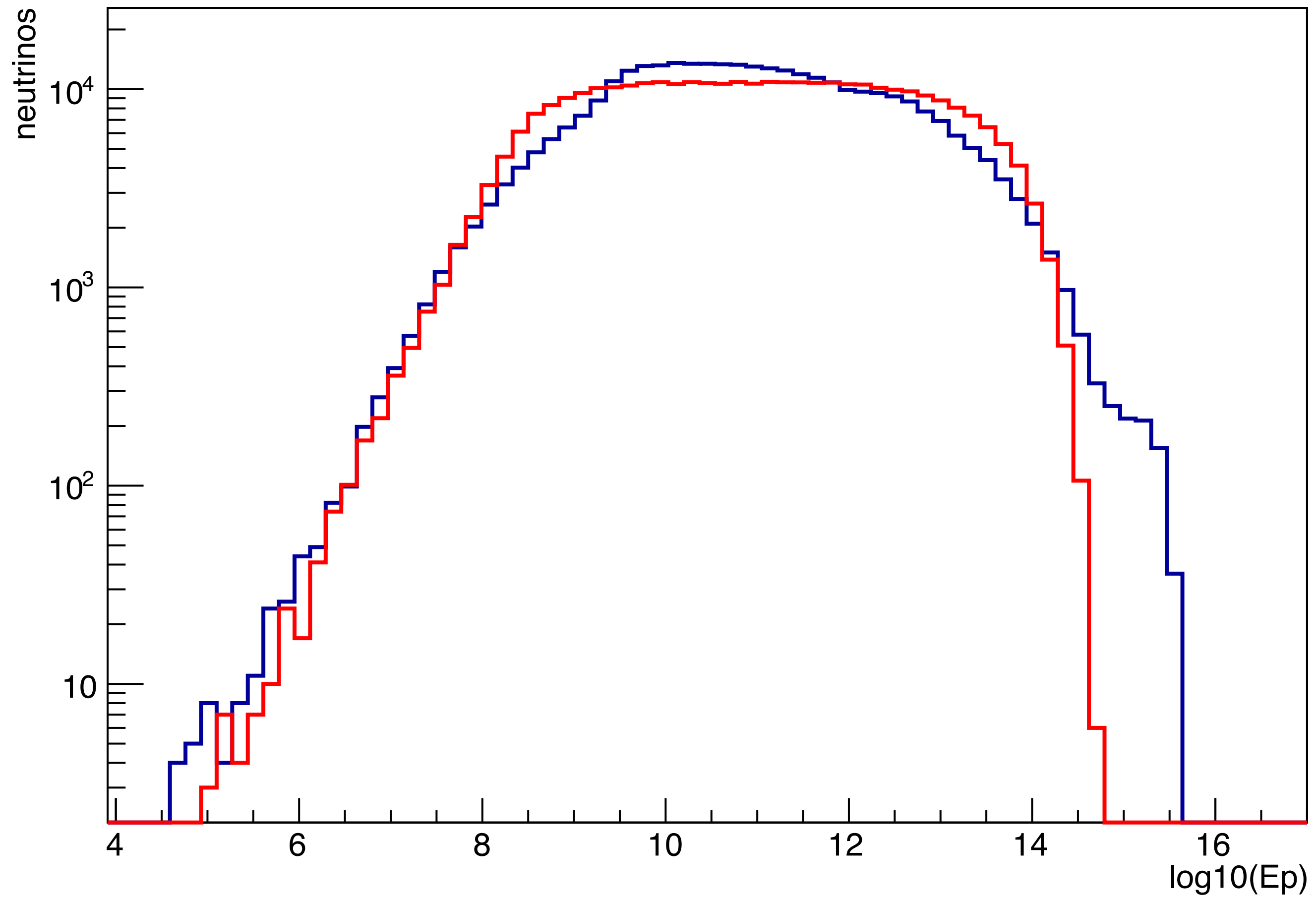
✴ Implementation of the photon field in the source;

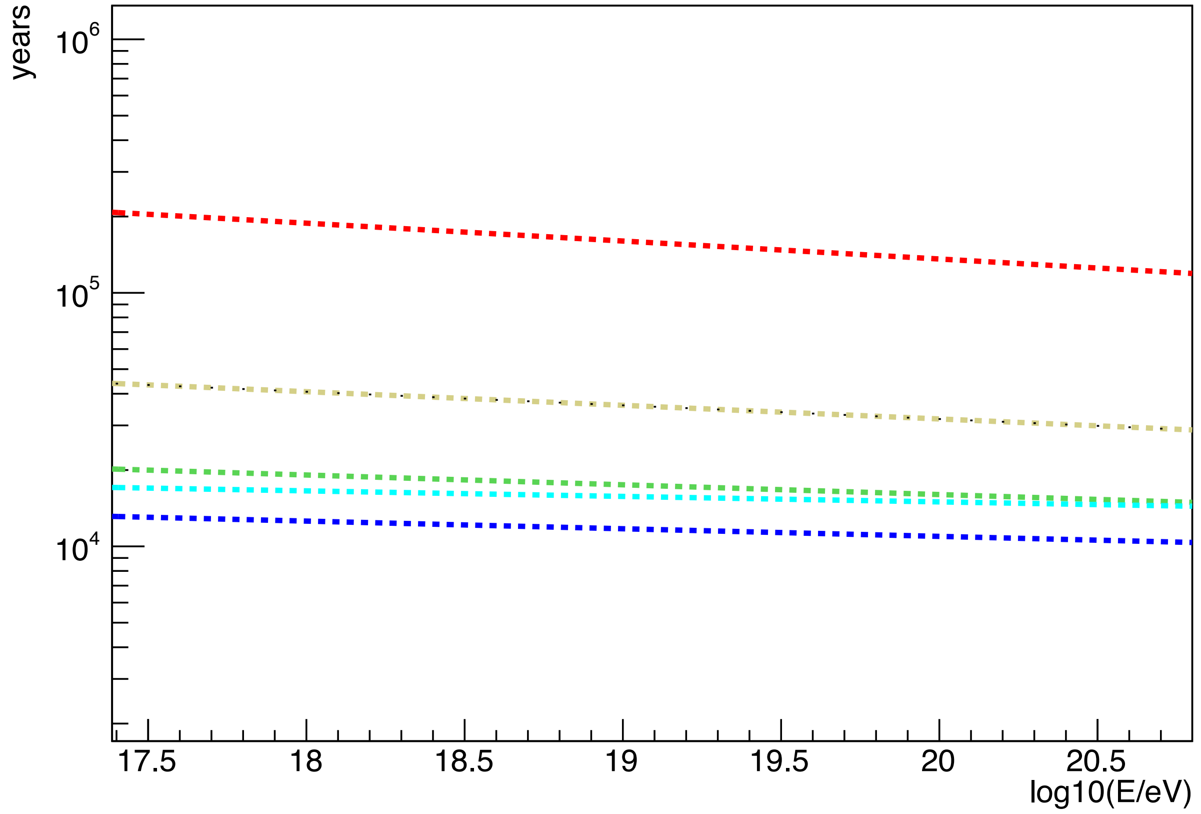
E. Peretti et al. Mon. Not. Roy. Astron. Soc. 487 (2019) no.1, 168-180

R. Aloisio et al. JCAP11(2017)009

Spallation time







Adapting SimProp (software for UHECRs propagation in extra-galactic space):

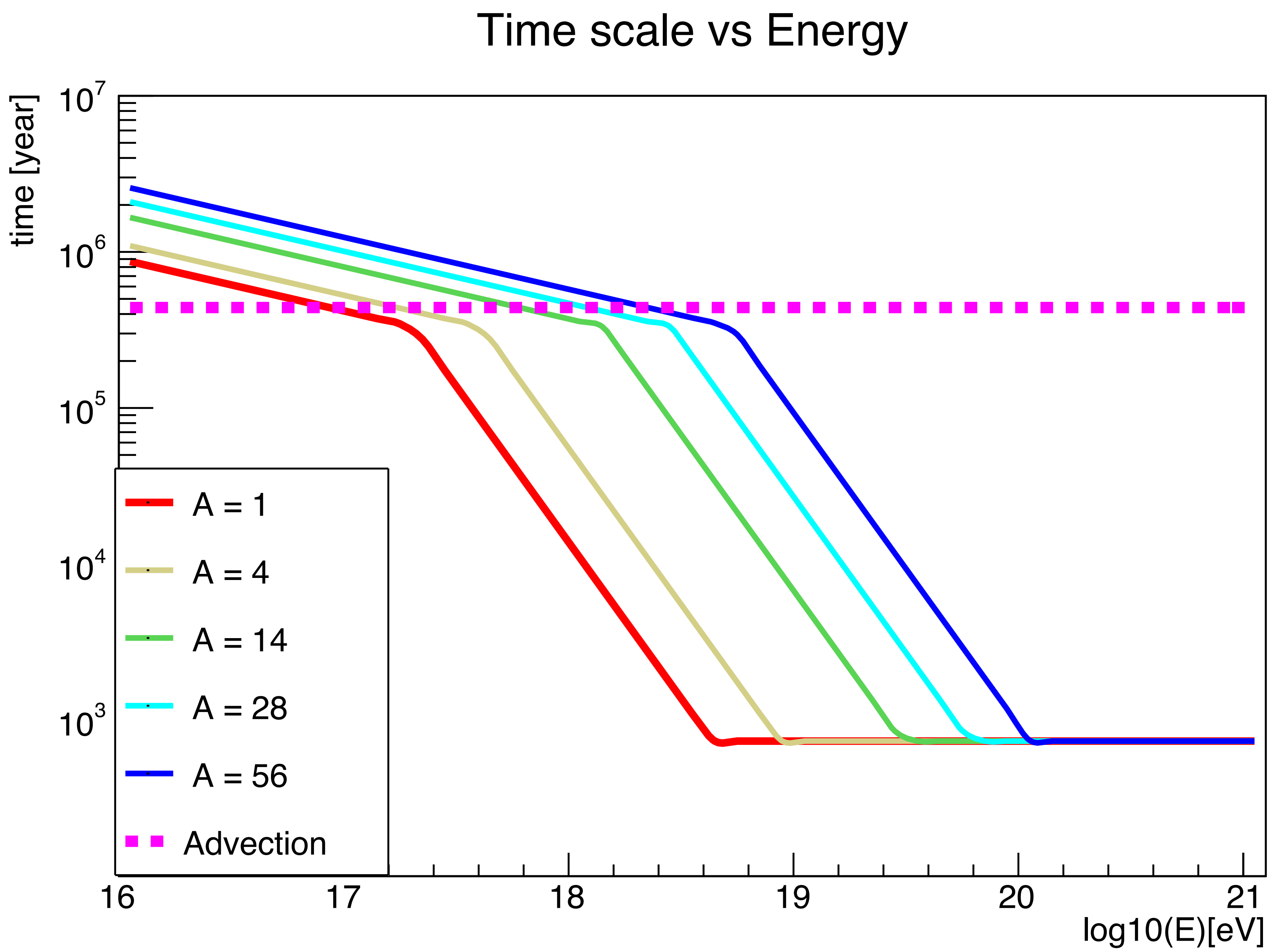
- ✴ Implementation of the photon field in the source;
- ✴ Implementation of the spallation process;

Escape time

Diffusion

$$\tau_D = \frac{R^2}{D}$$

Depends on the slope in energy and on the coherence lenght l_c



Advection

$$\tau_{\rm adv} = \frac{R}{v_w}$$

P. Subedi et al 2017 ApJ 837 140

Comparison to the experimental data

- A single nuclear specie (A = 28) is propagated inside the source. Sources are considered identical.

Comparison to the experimental data

- A single nuclear specie (A = 28) is propagated inside the source. Sources are considered identical.
- The escaping fluxes are propagated through the Universe.

Comparison to the experimental data

- A single nuclear specie (A = 28) is propagated inside the source. Sources are considered identical.
- The escaping fluxes are propagated through the Universe.
- The fluxes arriving in atmosphere are compared to the experimental data.

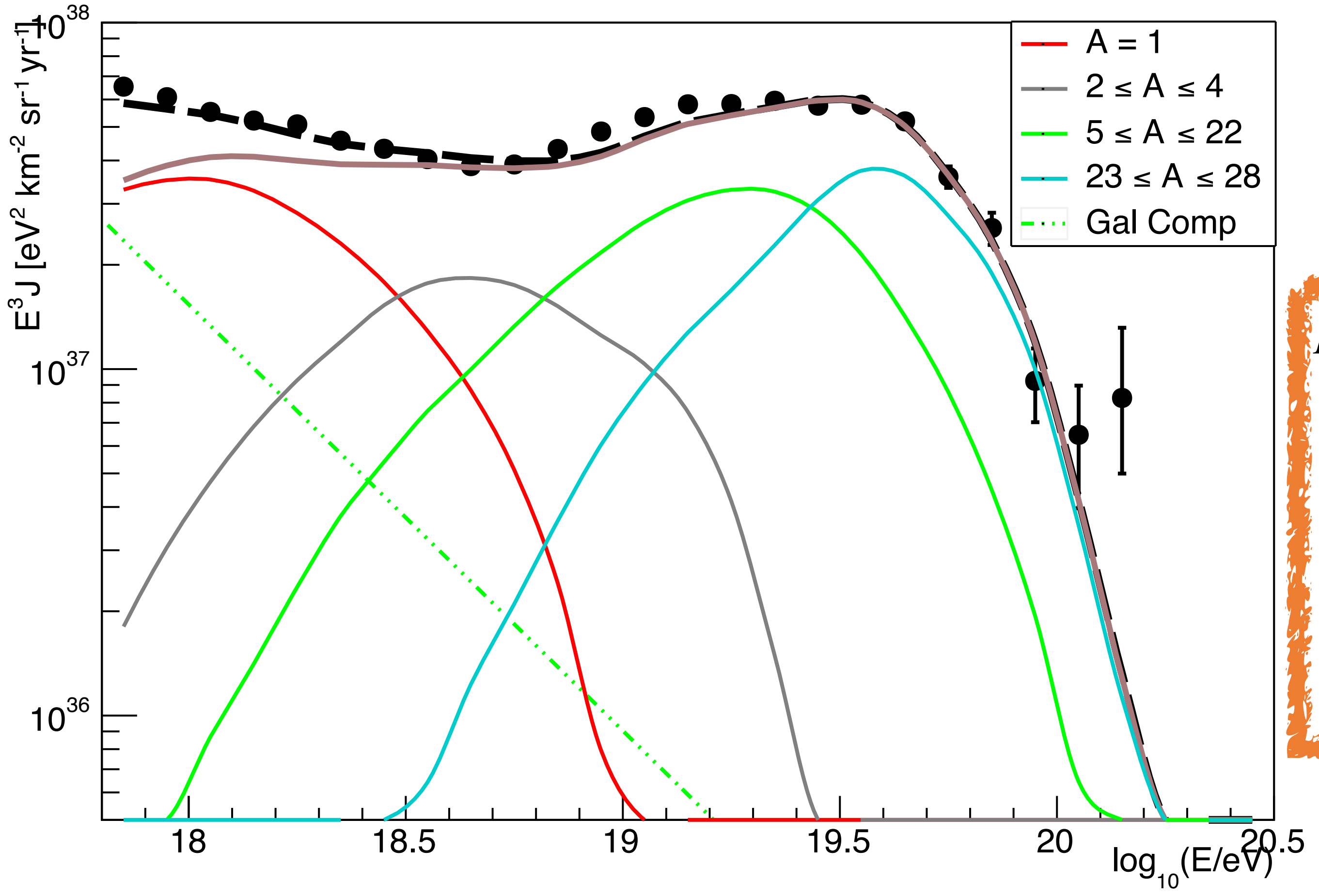
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

Comparison to the experimental data

- A single nuclear specie (A = 28) is propagated inside the source. Sources are considered identical.
- The escaping fluxes are propagated through the Universe.
- The fluxes arriving in atmosphere are compared to the experimental data.
- The chosen prototype is not able to describe the data at Earth.

Comparison to the experimental data

- A single nuclear specie (A = 28) is propagated inside the source. Sources are considered identical.
- The escaping fluxes are propagated through the Universe.
- The fluxes arriving in atmosphere are compared to the experimental data.
- The chosen prototype is not able to describe the data at Earth.
- Within the parameter space, a set of parameters at the source that can describe energy spectrum and composition at Earth was found.



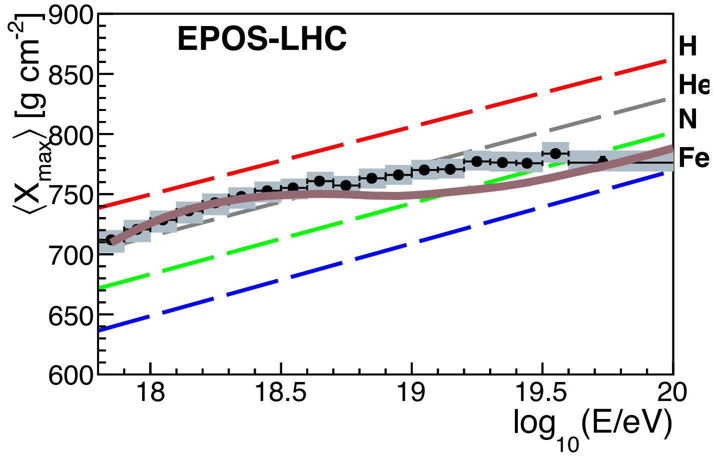
$L_{IR} = 3.46 \cdot 10^{45}$ erg/s

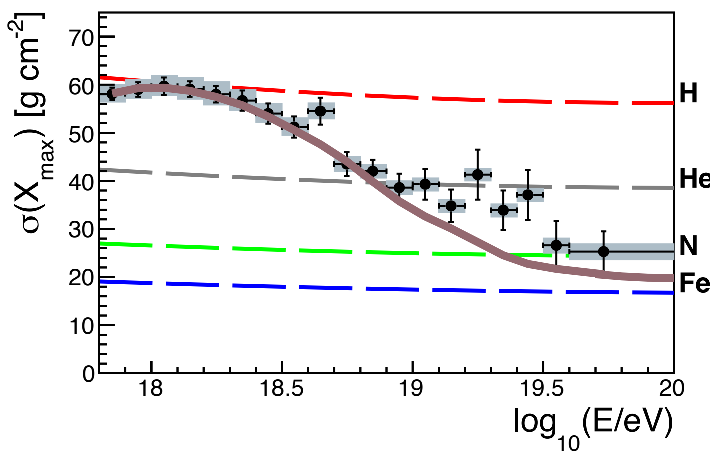
$R = 225$ pc

$n_{\rm ISM} = 1875\ {\rm cm}^{-3}$

$\gamma^* = 1$

$\log_{10}(R^*_{\rm cut}/V) = 18.5$

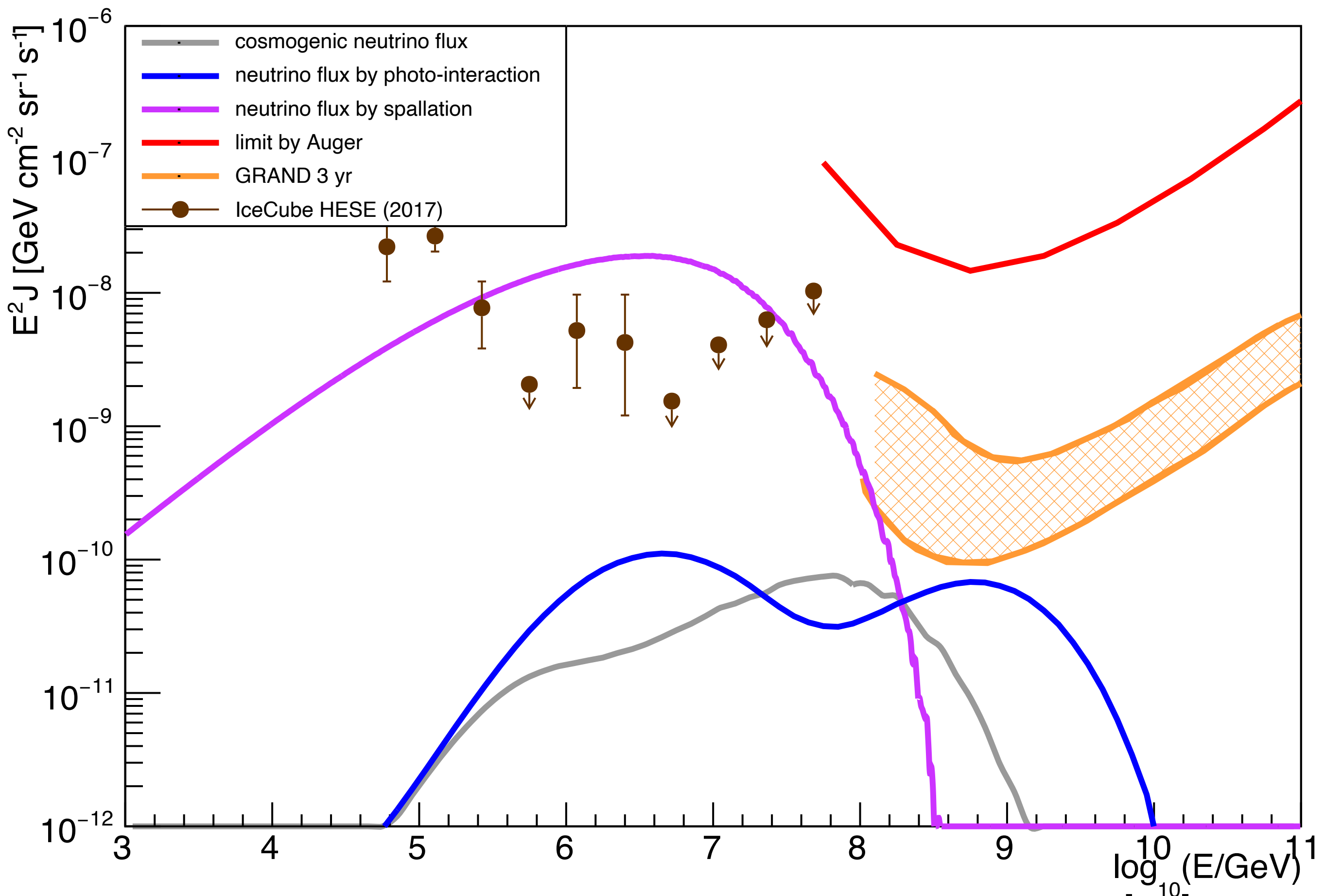




* assuming an injection shape $\frac{dN}{dE} \propto E^{-\gamma} \cdot f(E, Z \cdot R_{\rm cut})$

Associated neutrino fluxes

best case

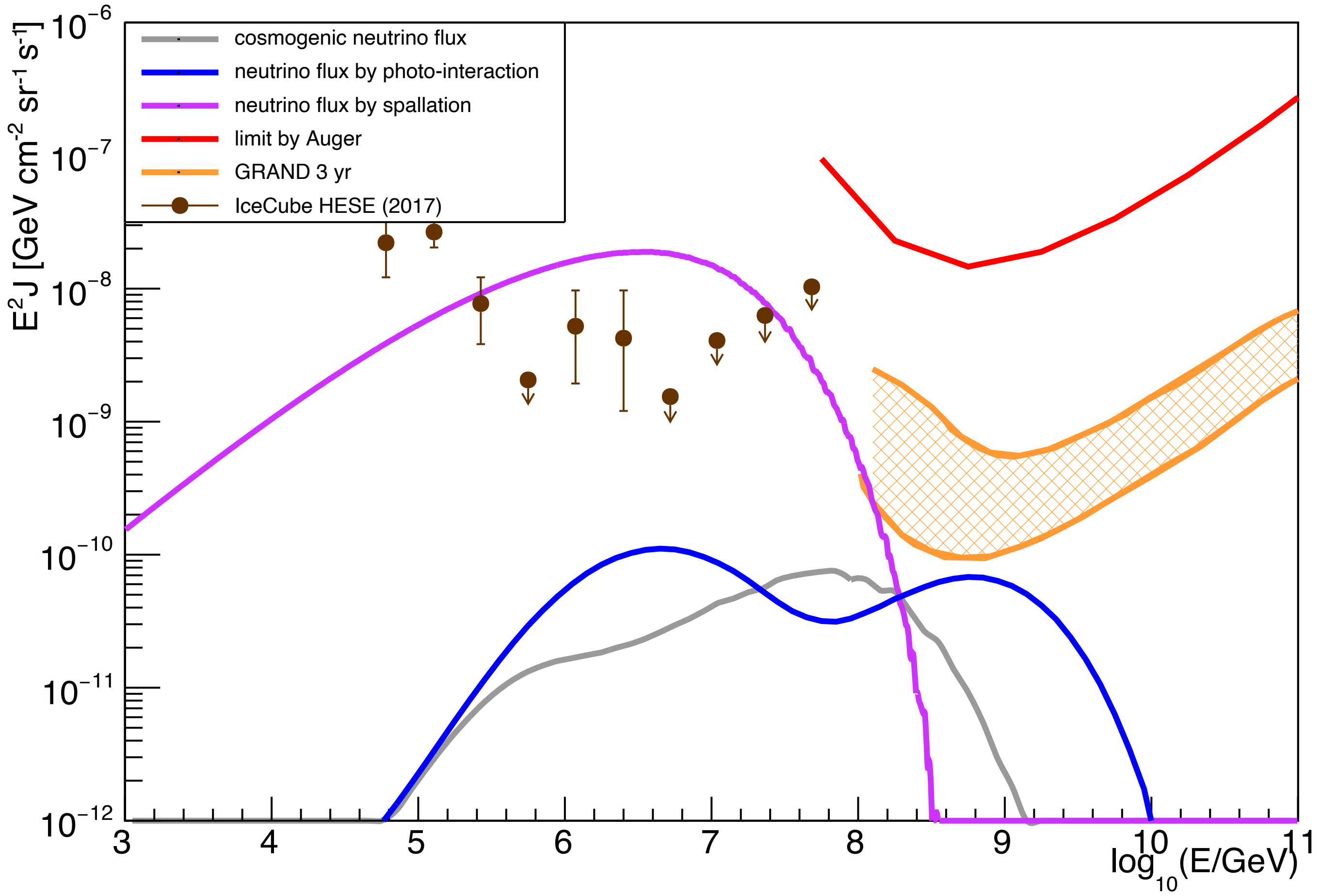


- Cosmogenic neutrinos are comparable to photo-interaction neutrinos produced in the source.
- Once taken into account also the hadronic interactions, the expected neutrino flux is larger and can be used to constrain plausible scenarios that describe the UHECR data.

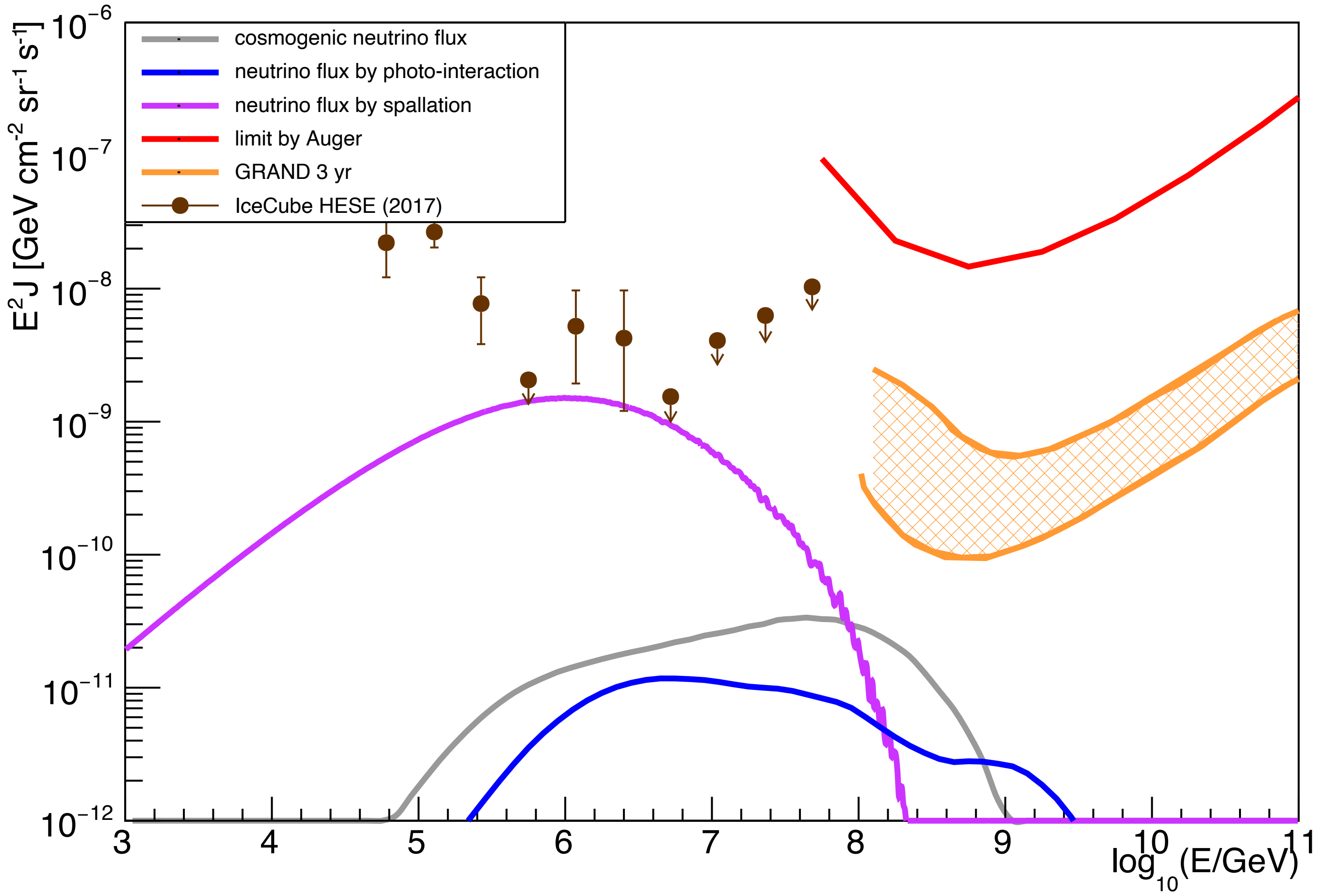
A.Condorelli, PoS(ICRC2021)959

Associated neutrino fluxes

best case



M82



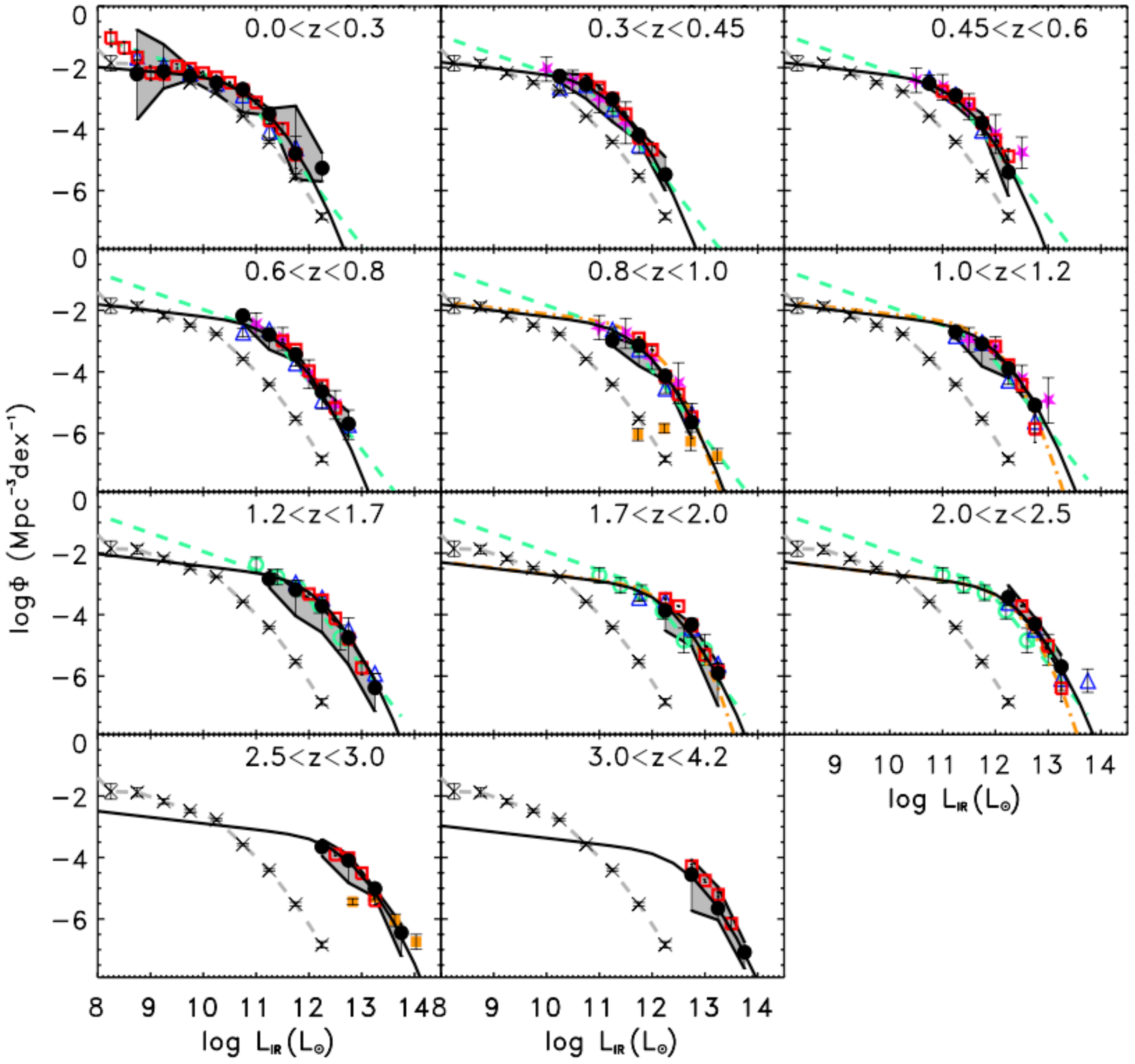
- Decreasing the luminosity, the neutrino fluxes from source decrease ;
- A detailed study of the parameter space is foreseen.

Cross-check on the number of sources

$$n_{SBG} = \frac{\varepsilon_{CR}}{\alpha \cdot L_{IR}} = 1.8 \cdot 10^{-6} \left[\frac{\alpha}{0.1}\right]^{-1} \mathrm{Mpc}^{-3}$$

From the comparison to the data

Cross-check on the number of sources



$$n_{\rm SBG} = \frac{\varepsilon_{\rm CR}}{\alpha \cdot L_{\rm IR}} = 1.8 \cdot 10^{-6} \left[\frac{\alpha}{0.1}\right]^{-1} \, {\rm Mpc}^{-3}$$

From the comparison to the data

Using the luminosity functions

$$n_{\rm SBG} \simeq 3 \cdot 10^{-5} \, {\rm Mpc}^{-3}$$

G. Gruppioni et al,
DOI: https://doi.org/10.1093/mnras/stt308

Summary and future perspectives

- [x] Source-propagation model in a Starburst Galaxy : M82;
- [x] Computing interaction and escape times;
- [x] Exploring the parameter space in order to describe both the energy spectrum and composition;
- [x] Cosmogenic and source neutrino fluxes for each configuration;
- [x] Cross-check on the number of sources using luminosity functions.

- [ ] Re-running the analysis using Sibyll2.3d.
- [ ] Paper in preparation..stay tuned!

Summary and future perspectives

- ☑ Source-propagation model in a Starburst Galaxy : M82;
- ☑ Computing interaction and escape times;
- ☑ Exploring the parameter space in order to describe both the energy spectrum and composition;
- ☑ Cosmogenic and source neutrino fluxes for each configuration;
- ☑ Cross-check on the number of sources using luminosity functions.

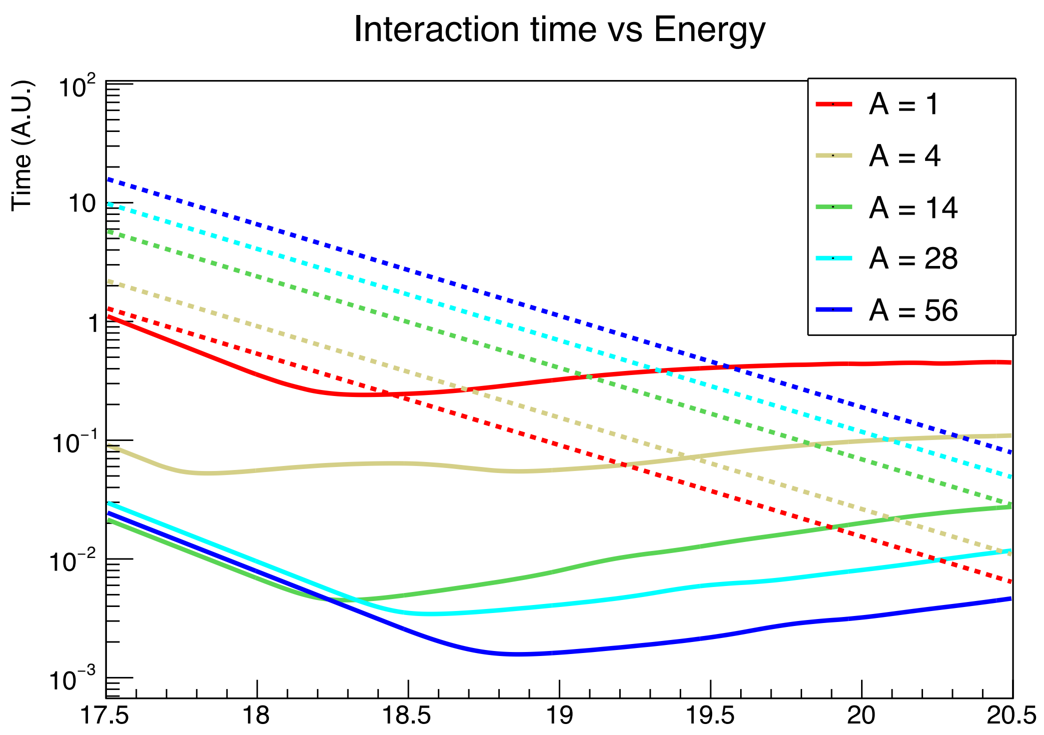
- ☐ Re-running the analysis using Sibyll2.3d.
- ☐ Paper in preparation..stay tuned!

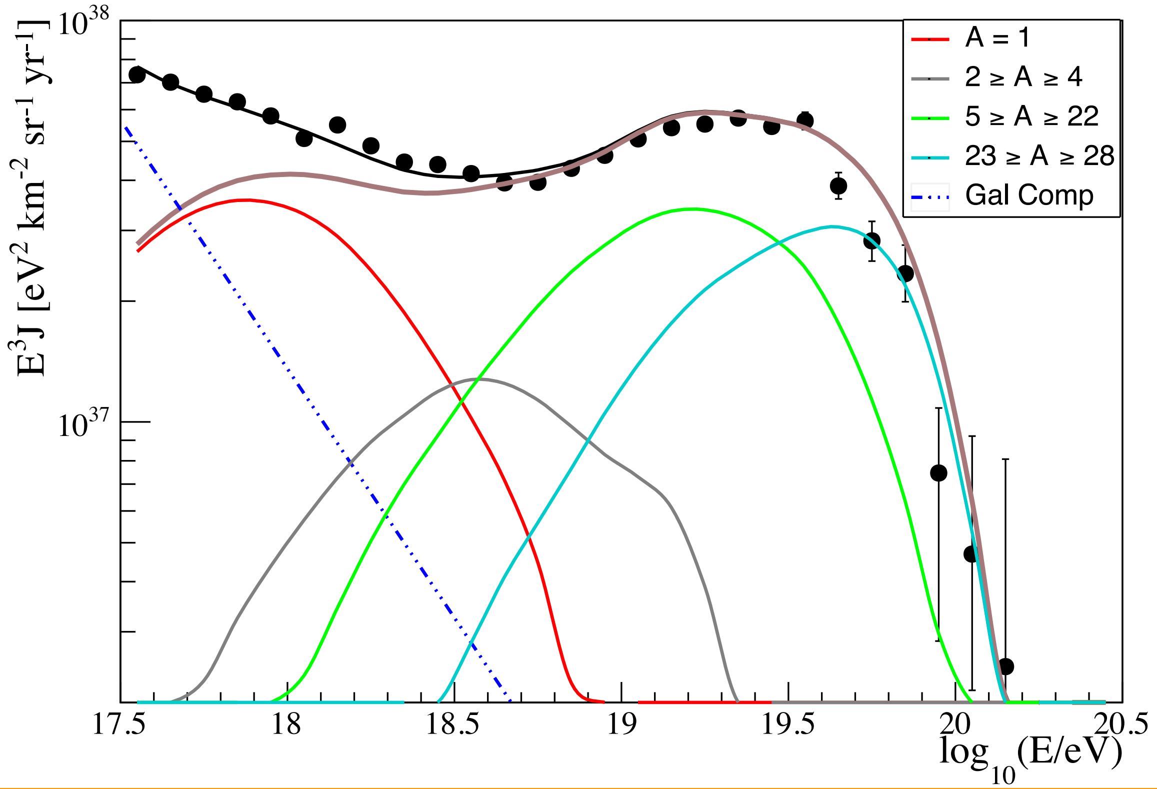
Merci pour votre attention!

Back-up slides!

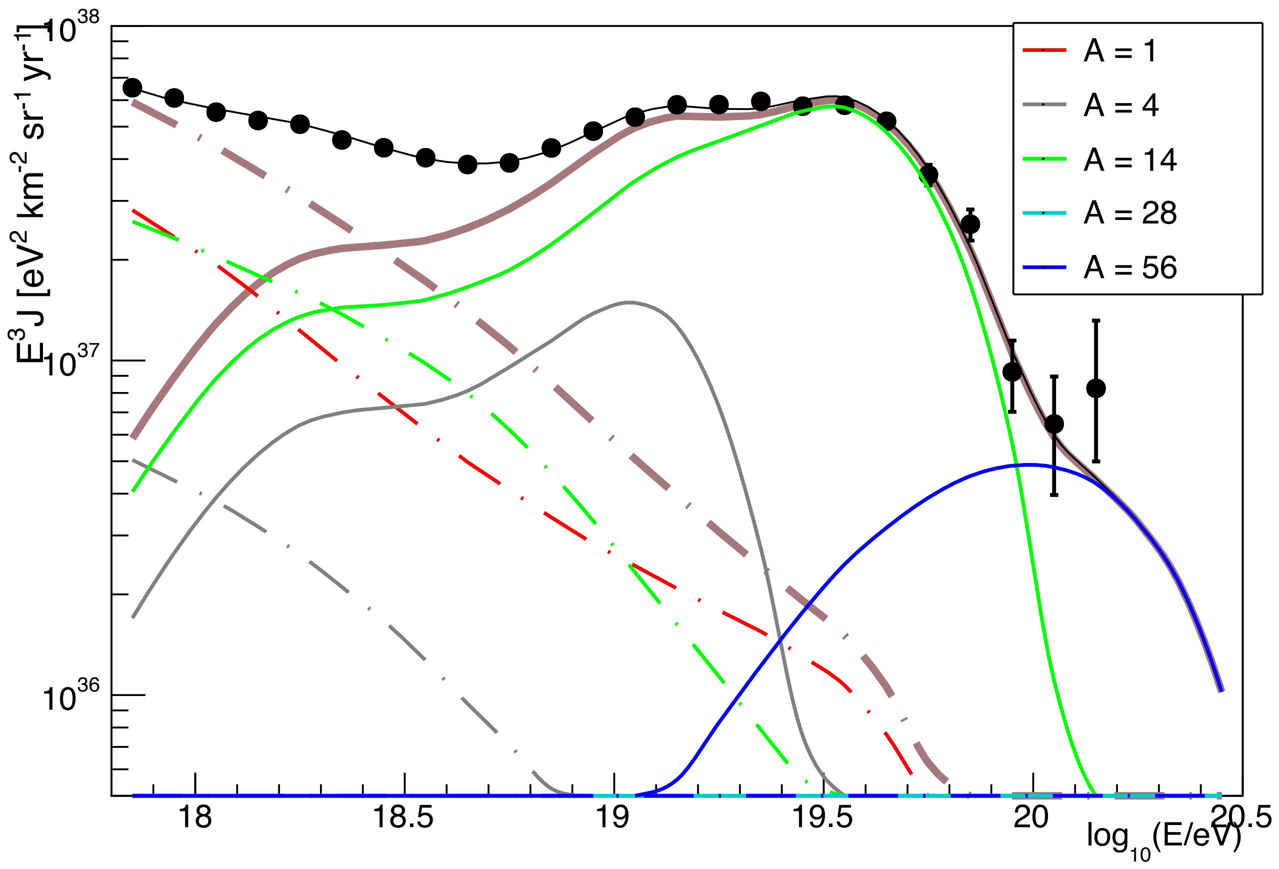
Methodology of source-propagation model

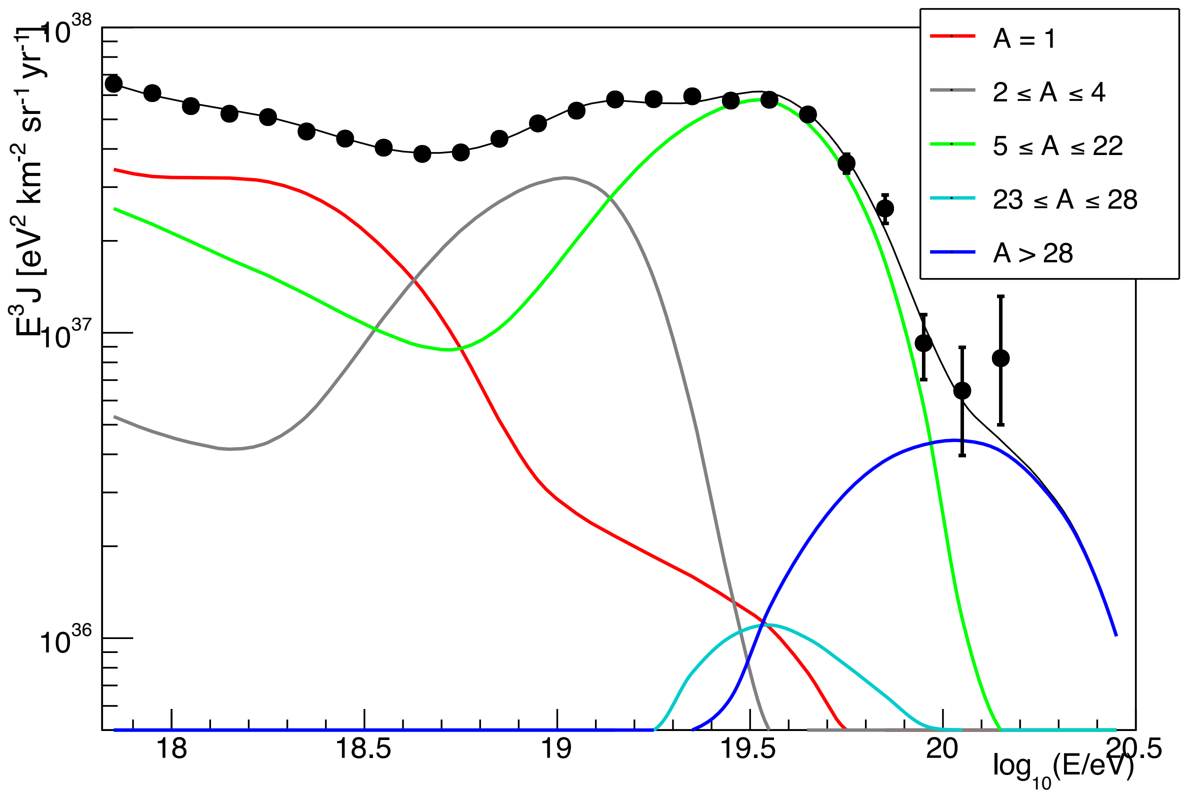
- A single nuclear specie is injected in the environment surrounding the source;
- Interaction and escaping times are computed: if a particle escapes is not propagated anymore, otherwise the computation of energy and mass losses is performed;
- We are assuming that all the sources are identical and distributed up to a maximum redshift.
- The fluxes escaping from the sources are propagated thought the extra-galactic space and compared to the da at Earth.

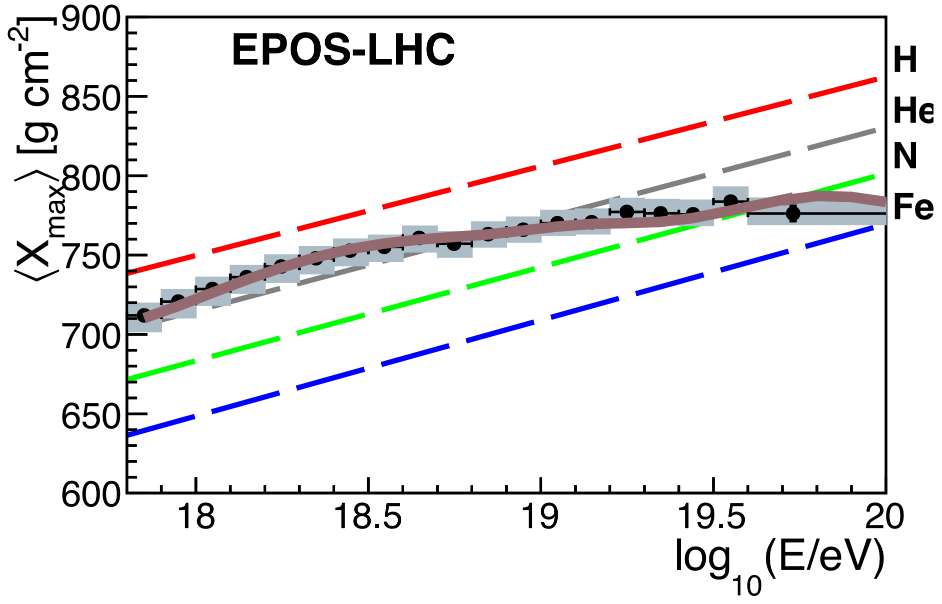


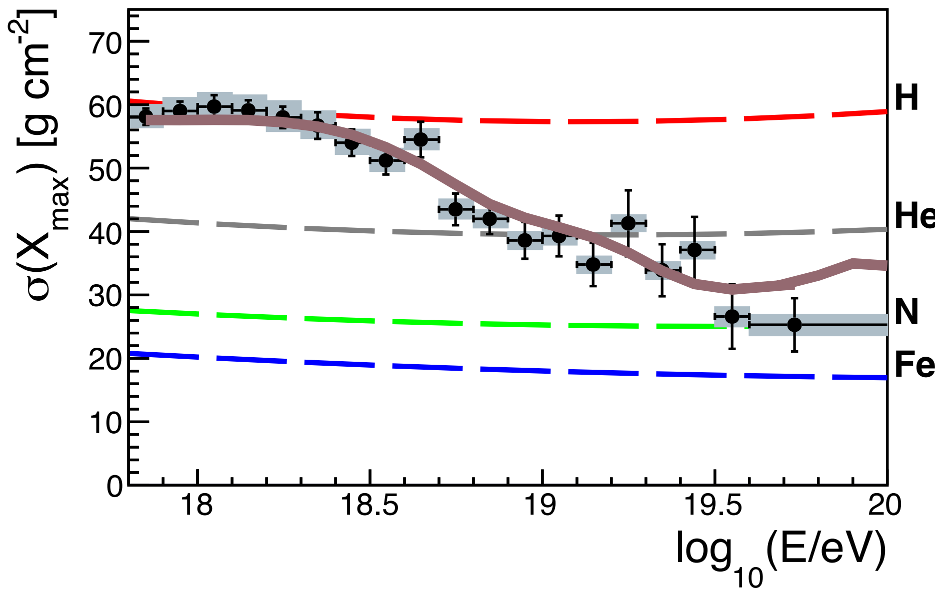


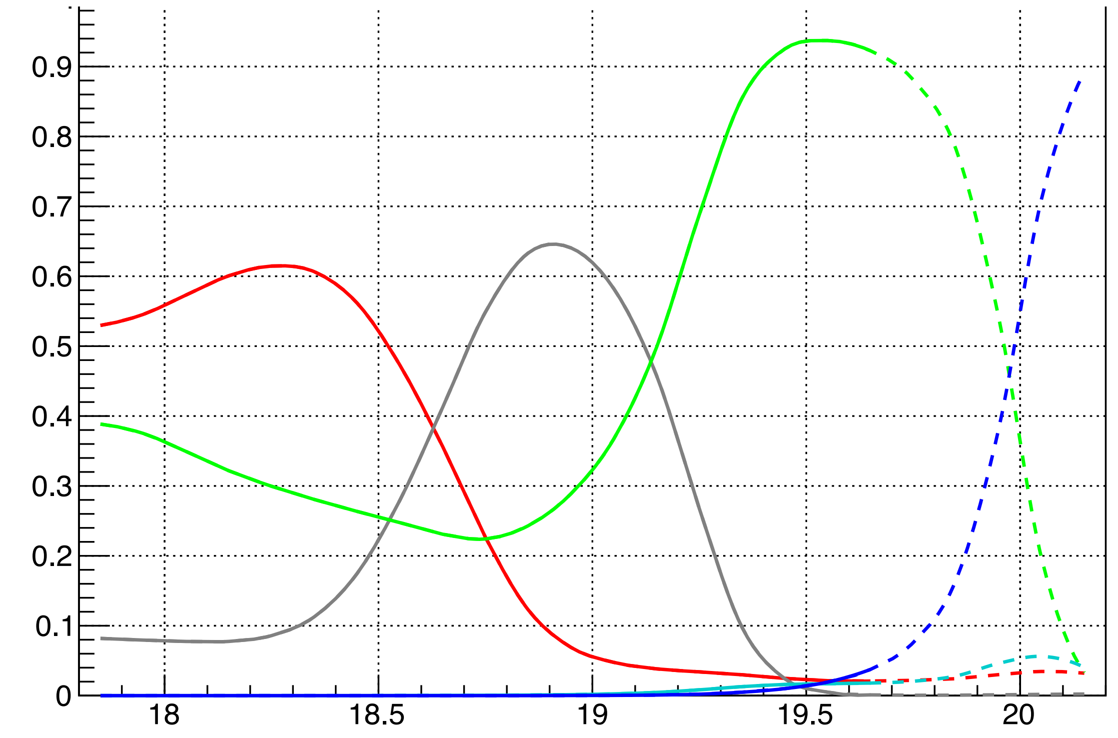
Second extra-galactic component











Combined fit above the ankle: ingredients

- Assuming point-like sources identical and uniformly distributed;
- Acceleration of five representative masses: Hydrogen, Helium, Nitrogen, Silicon and Iron.
- The injected flux for each mass is a power law with a broken-exponential cutoff.

$$J_k(E_i) = f_k J_0 \left(\frac{E_i}{E_0}\right)^{-\gamma} \cdot f_{\text{cut}}(E_i, Z \cdot R_{\text{cut}})$$

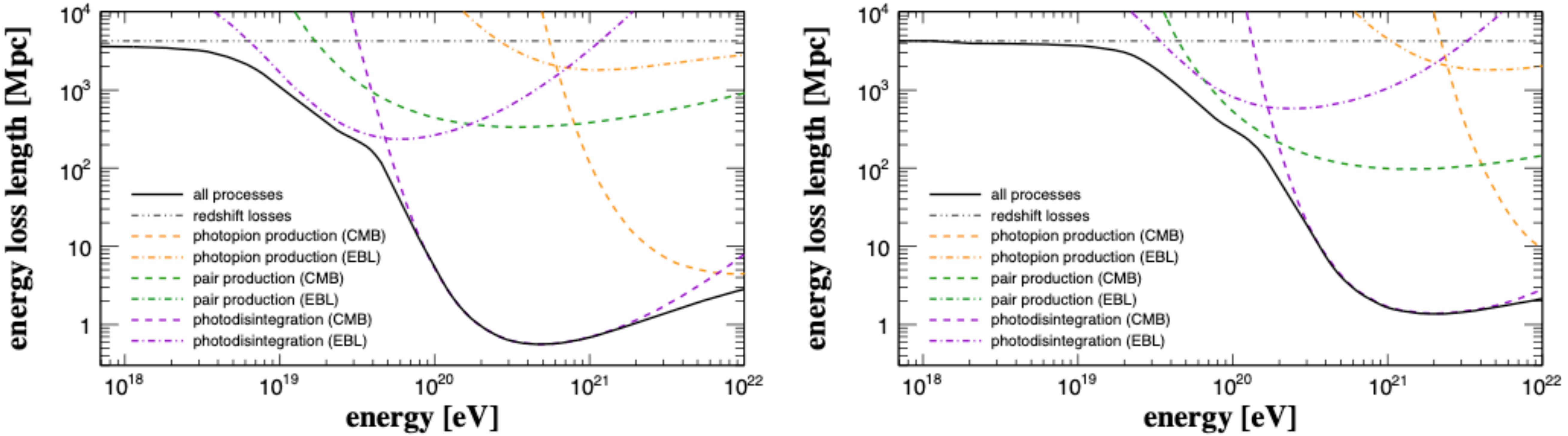
$$f_{\text{cut}}(E_i, Z \cdot R_{\text{cut}}) = \begin{cases} 1 & E_i < Z\ R_{\text{cut}} \\ \exp\left(1 - \frac{E_i}{Z \cdot\ R_{\text{cut}}}\right) & E_i > Z\ R_{\text{cut}} \end{cases}$$

- The injected flux are propagated through the extra-galactic space and fitted to the Auger energy spectrum and composition.
- Free parameters of the fit are: $J_0, \gamma, R_{\text{cut}}$ and $(N-1)\ f_k$.
- The total deviance is considered as the sum of the deviance of the spectrum and the deviance of the composition.

A.Aab et al. (The Pierre Auger Collaboration), JCAP04(2017)038

Simulation of extra-galactic propagation

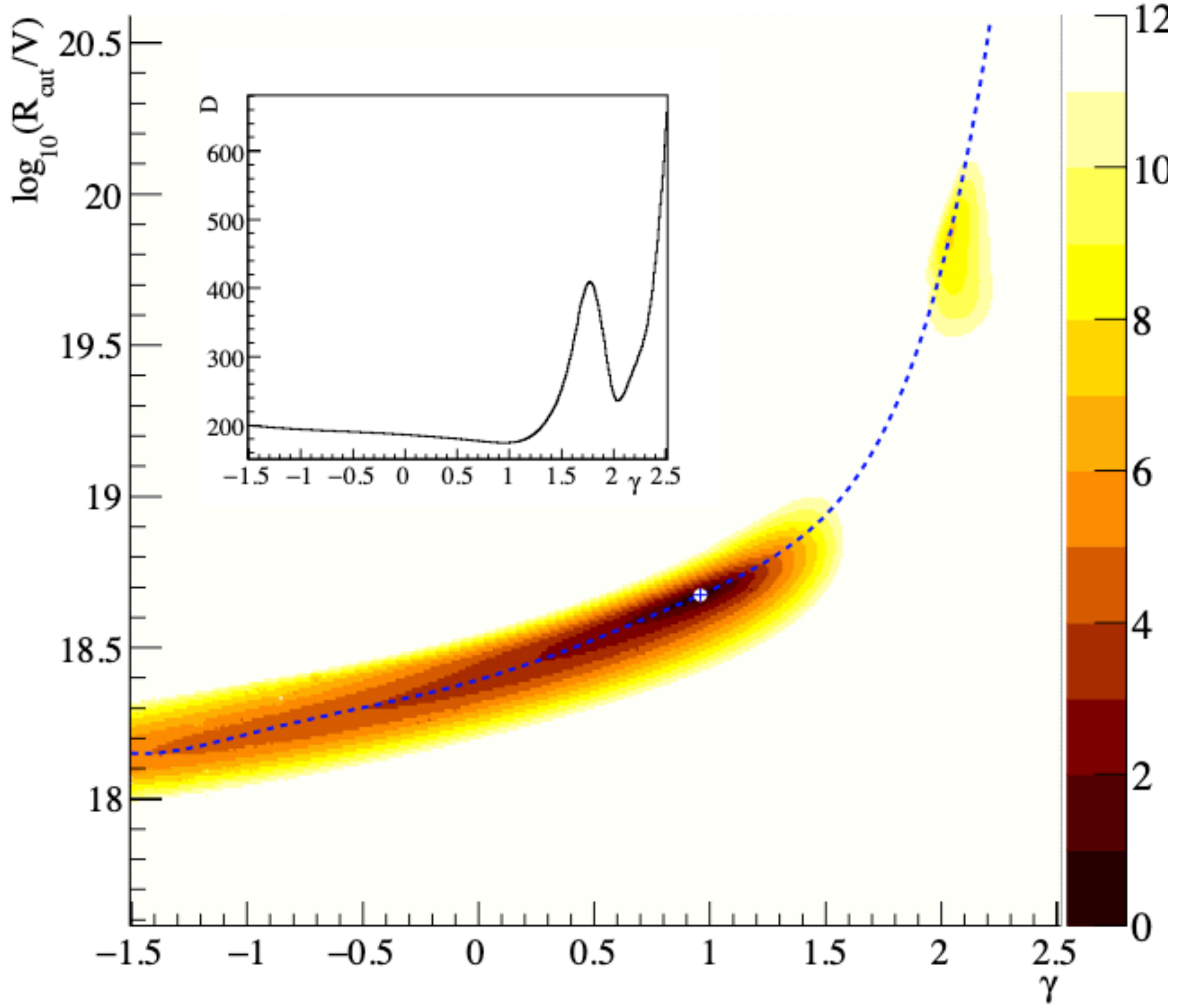
To interpret the measured spectrum and mass composition data in terms of astrophysical scenarios, some tools are needed in order to take into account the role of the propagation.

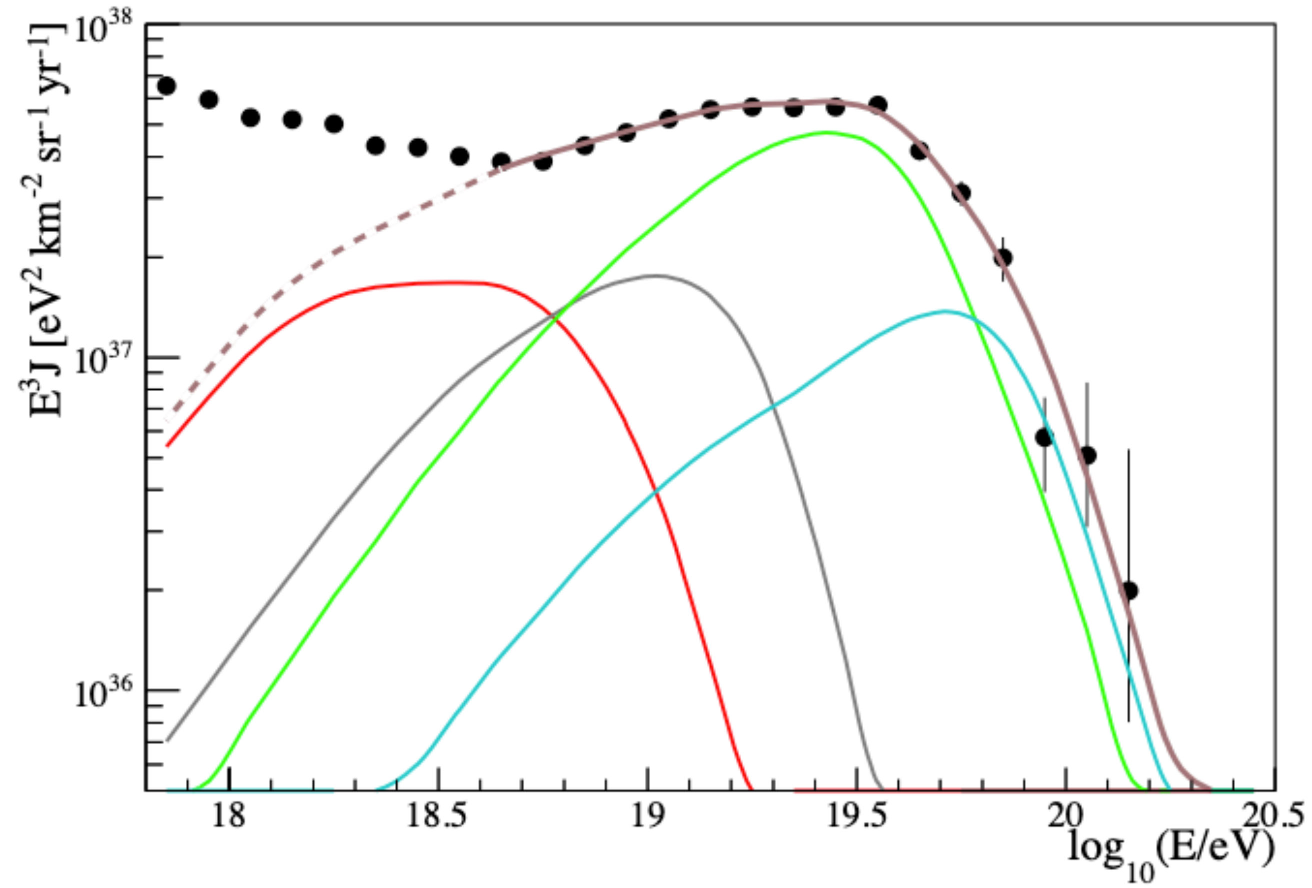


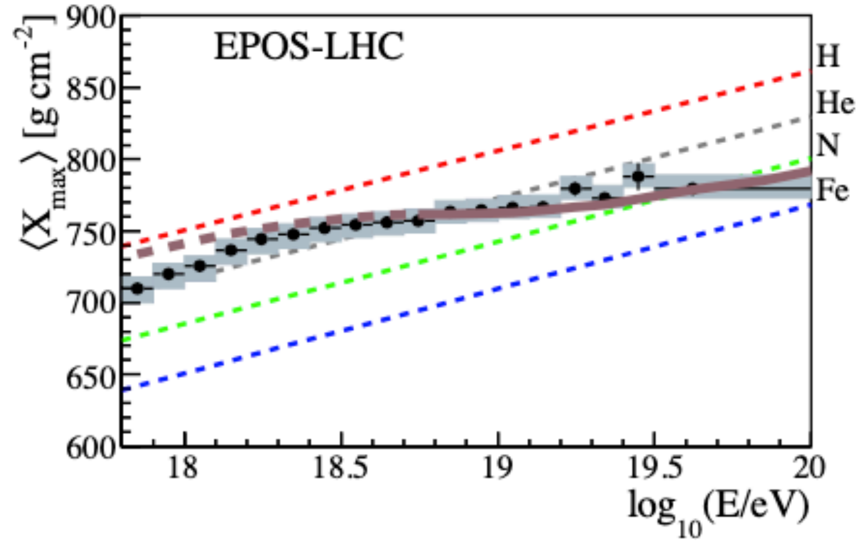
The SimProp software

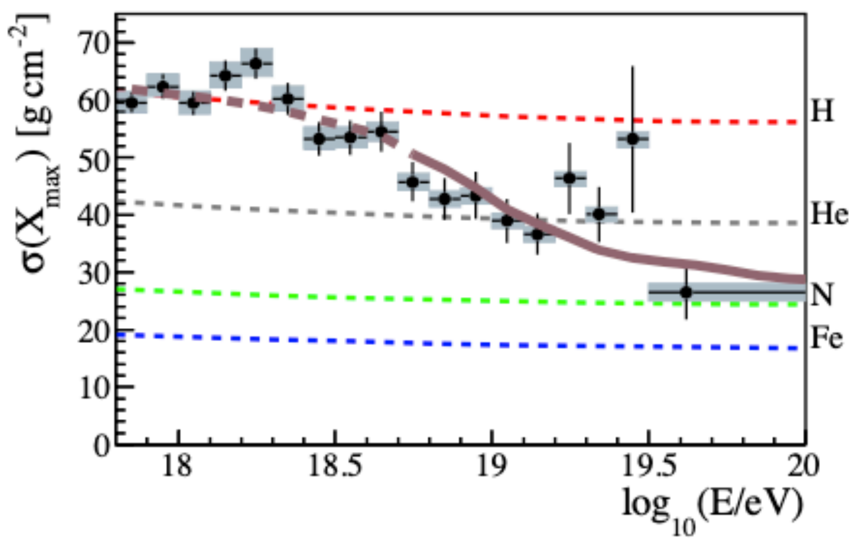
- SimProp is a Monte Carlo simulation code for the propagation of UHECRs through the Universe.
- Particles injected with a flat distribution in energy and source redshift uniformly distributed.
- The propagation of particles is followed, along with that of the secondary particles produced during propagation.
- Different models for the Photo-disintegration cross section and EBL model.

Combined fit above the ankle: results



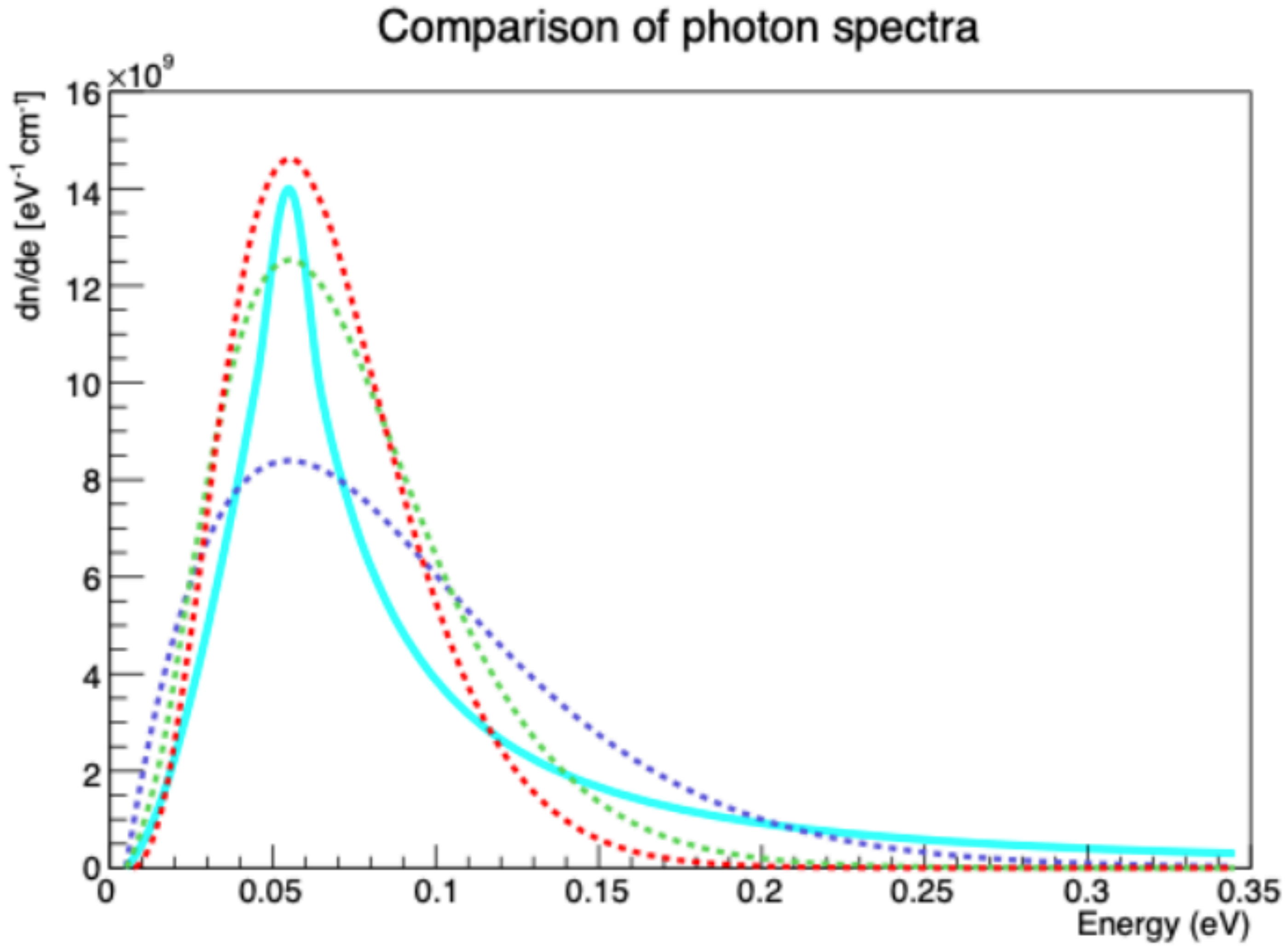


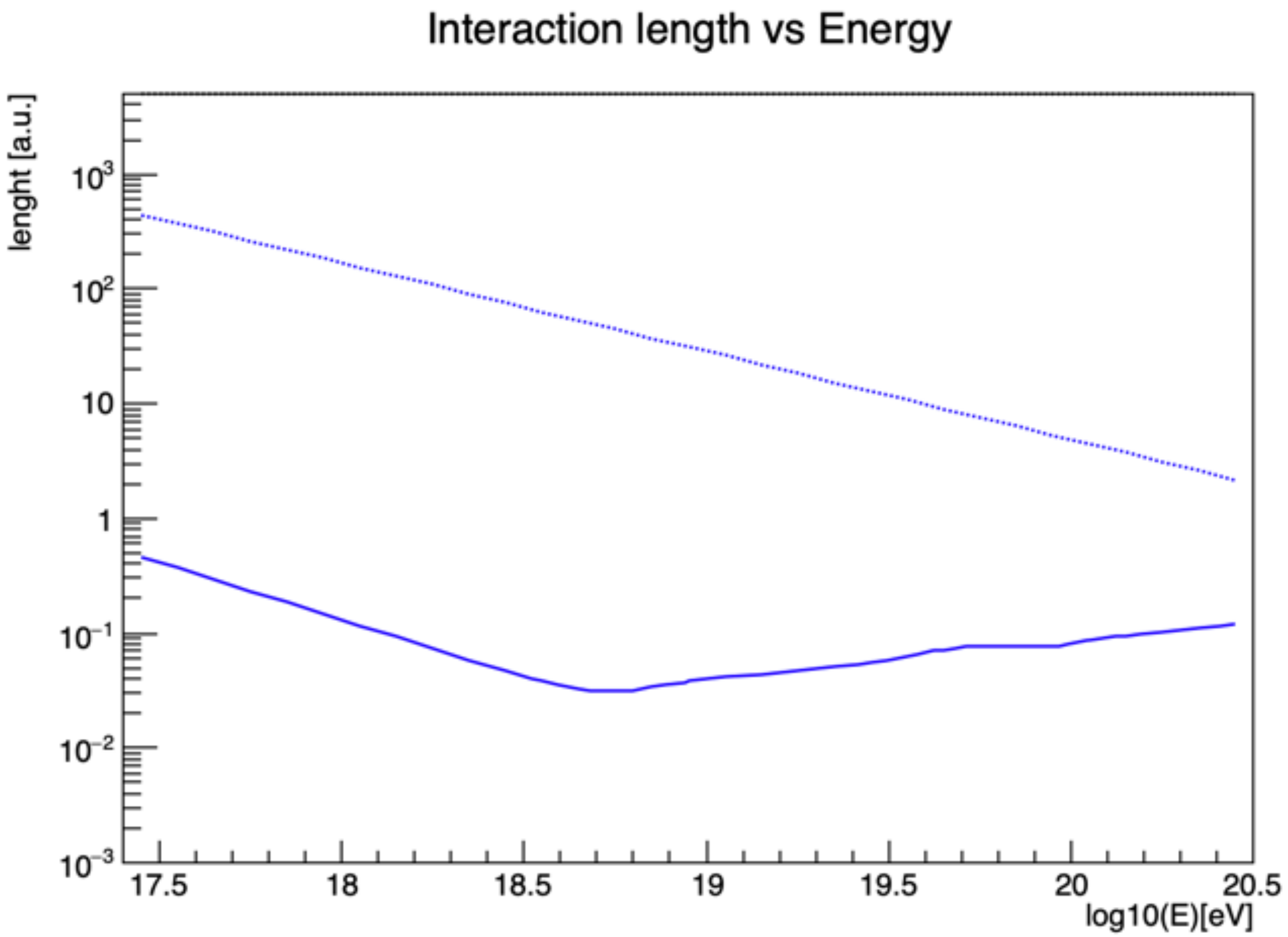




A.Aab et al. (The Pierre Auger Collaboration), JCAP04(2017)038

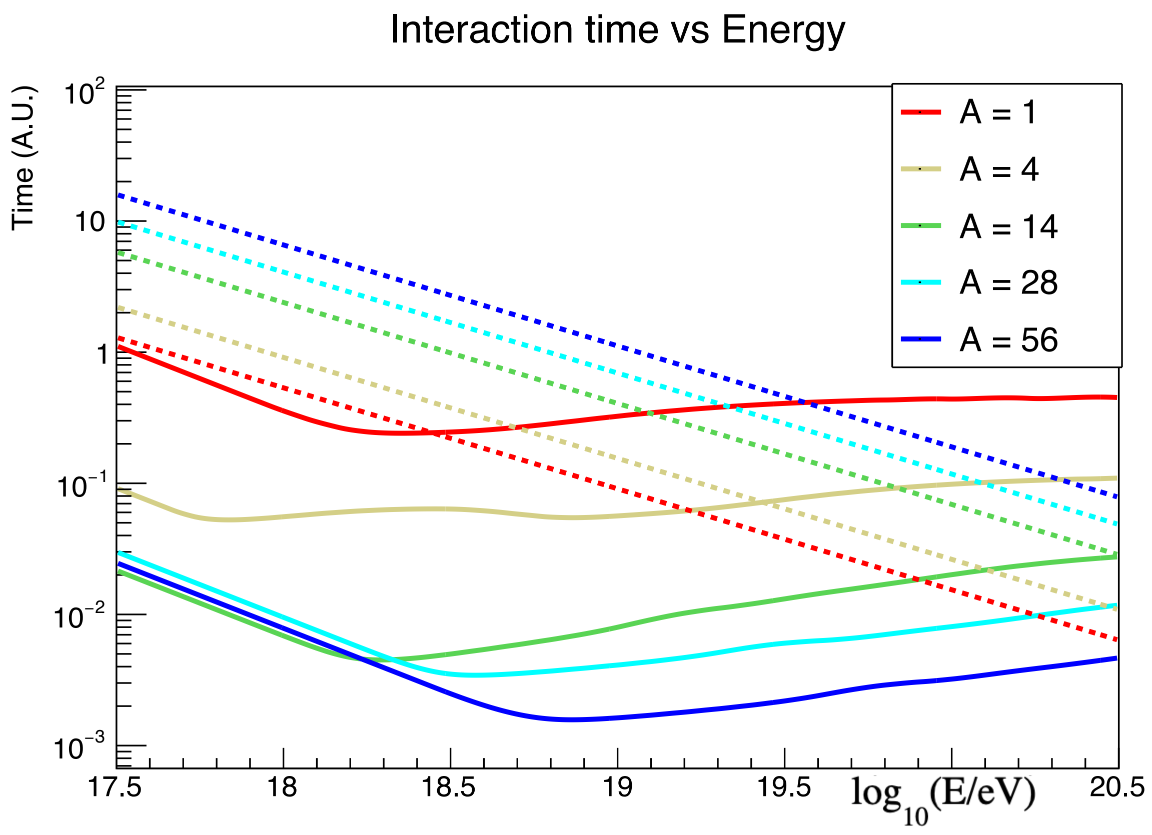
UFA model

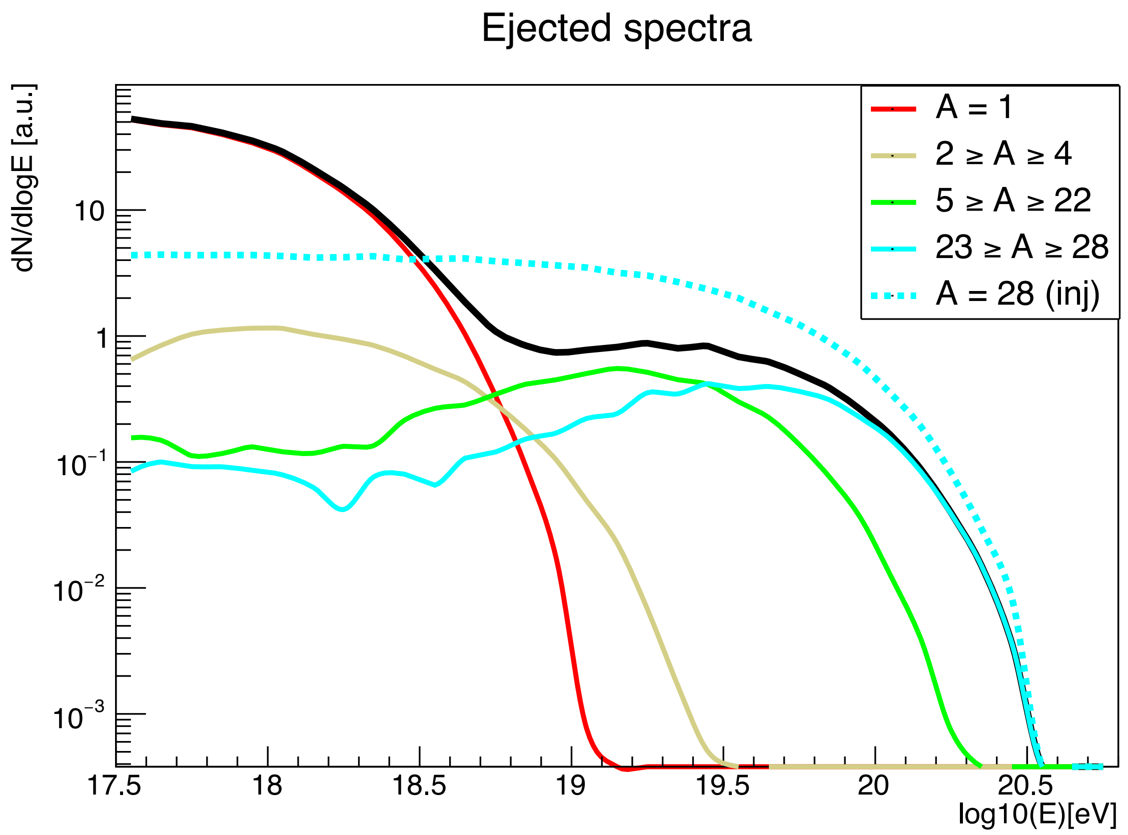


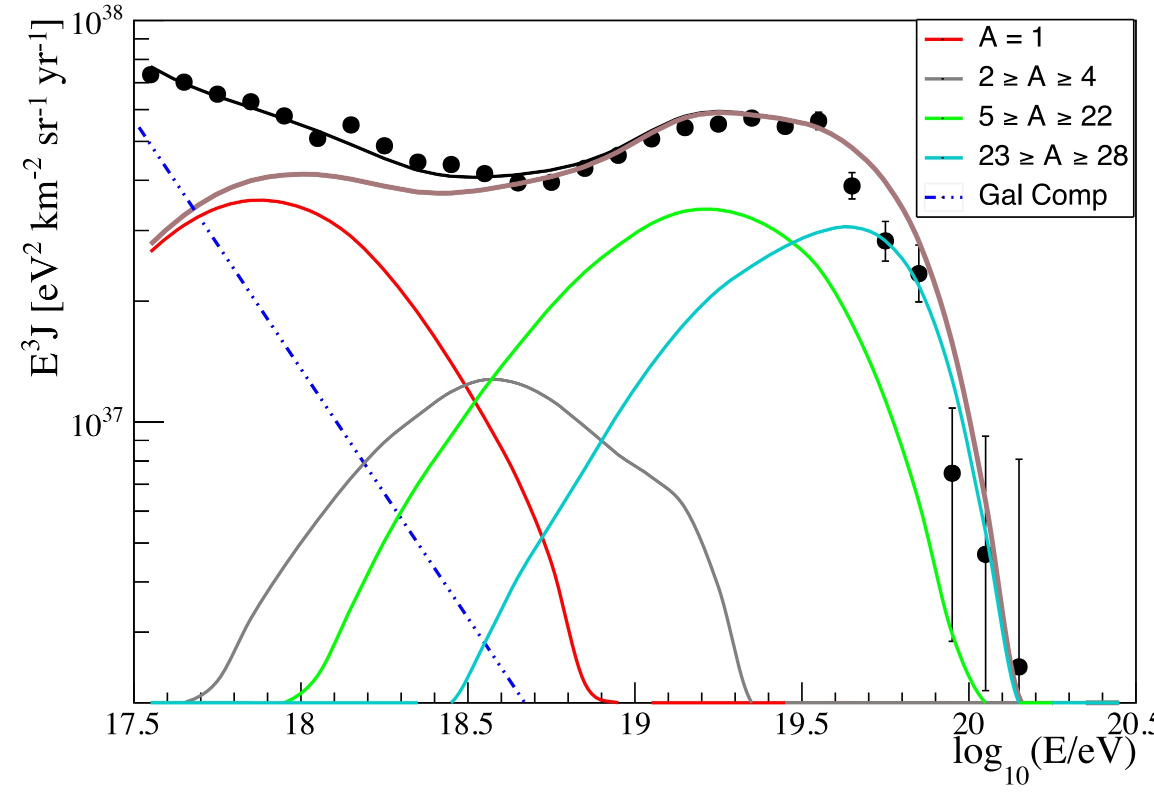


$$\frac{1}{\tau} = \frac{1}{2\Gamma^2} \int_{\epsilon'_{\min}}^{2\Gamma\epsilon} \int_{\epsilon=0}^{+\infty} \frac{n_\gamma(\epsilon)}{\epsilon^2} \, \mathrm{d}\epsilon \, \sigma(\epsilon')\epsilon' \, \mathrm{d}\epsilon'$$

UFA model



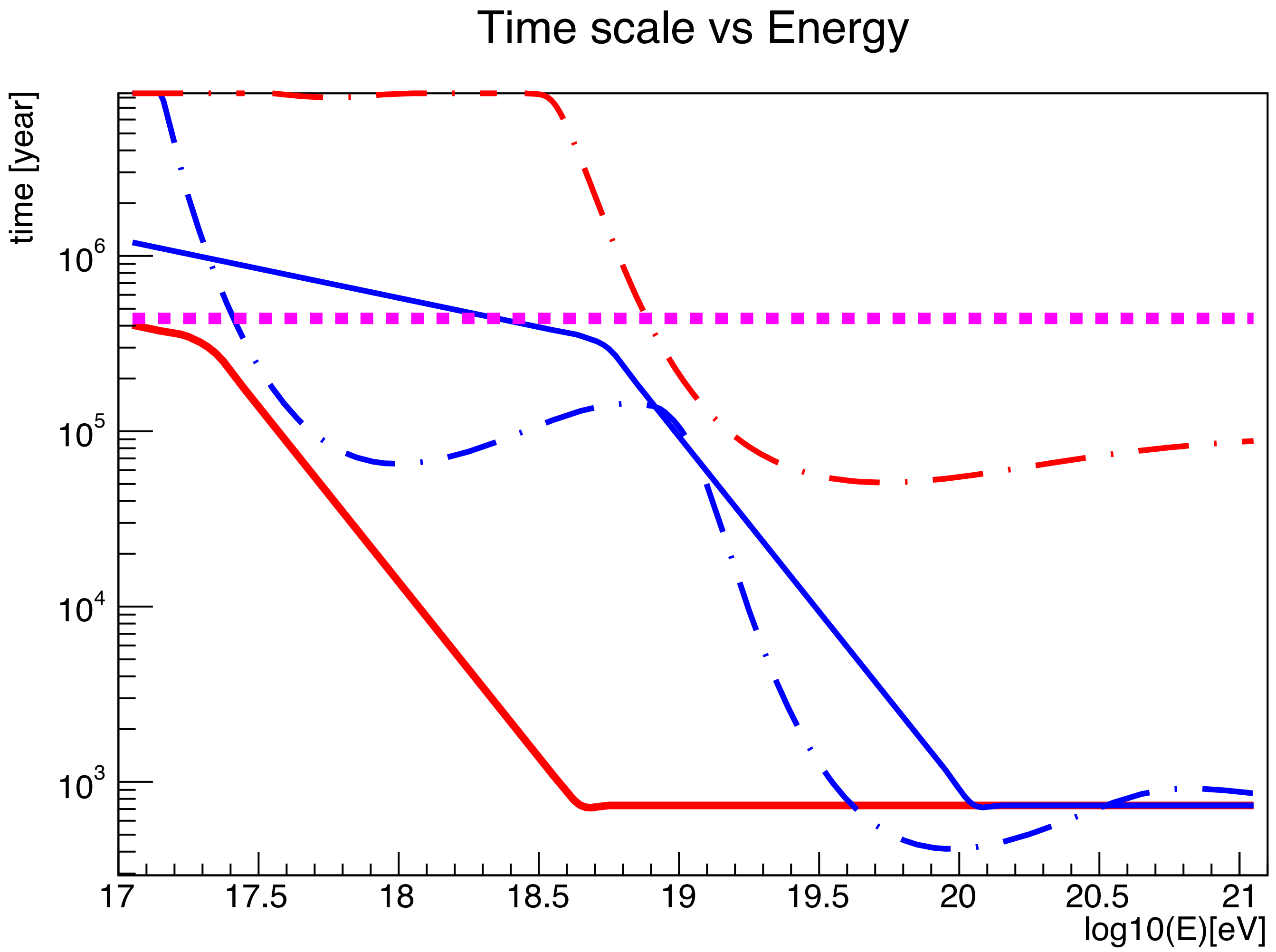


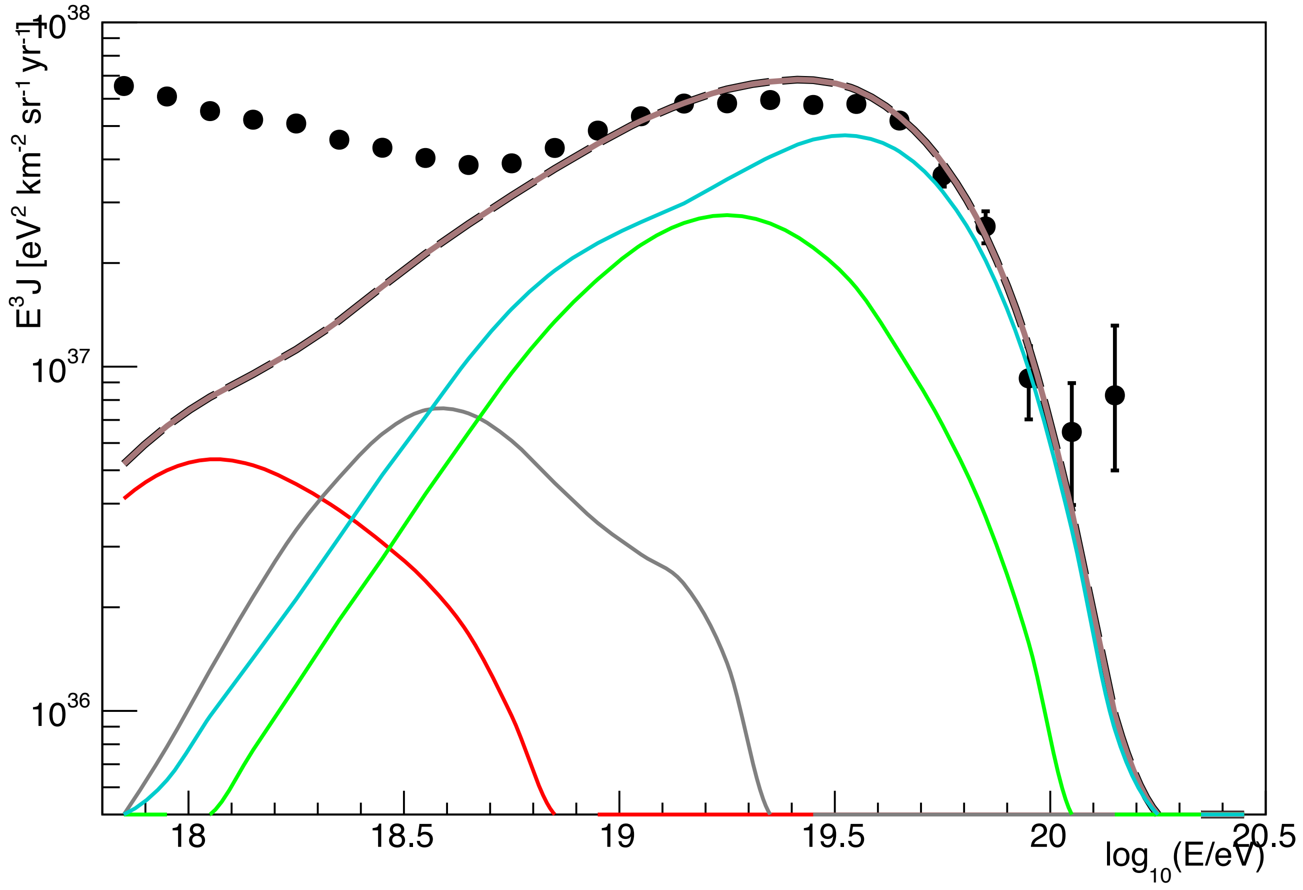


M. Unger, G.R. Farrar and L.A. Anchordoqui, Phys. Rev. D 92, 123001 (2015)

M82 test

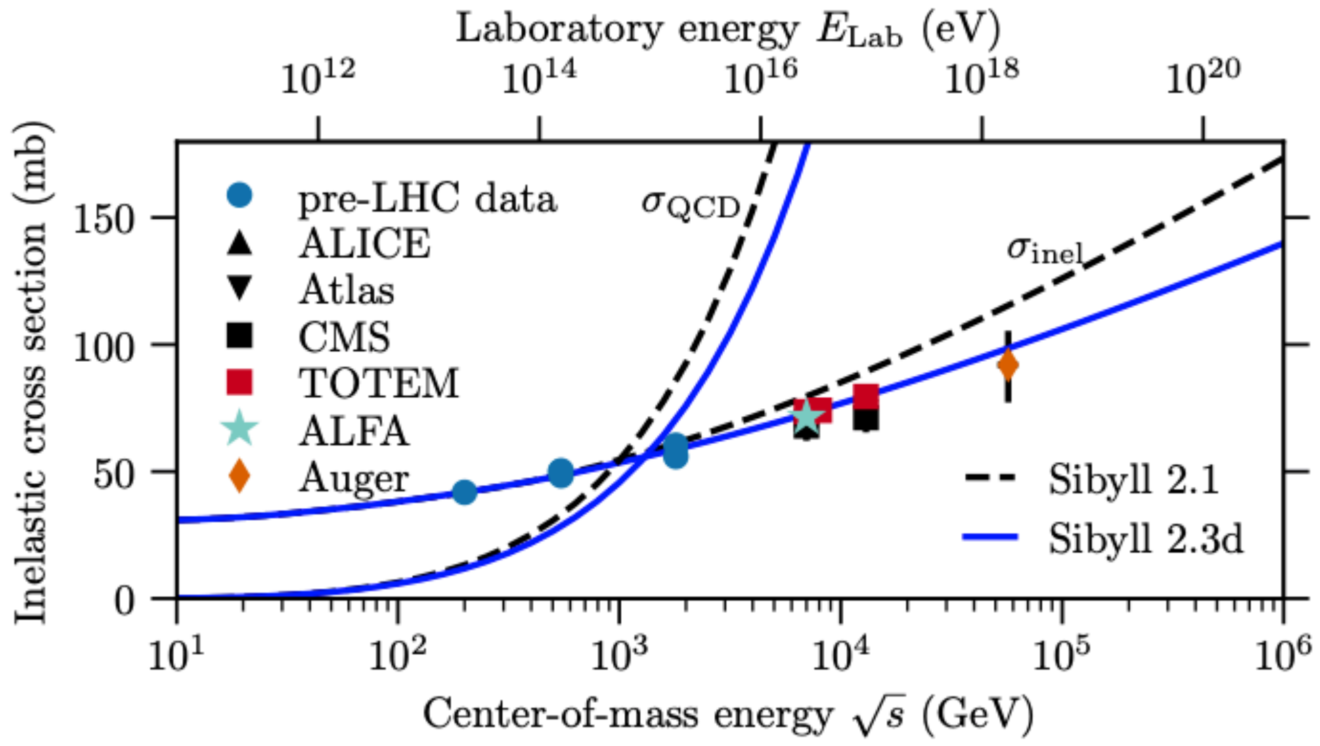
Using the starting prototype a good agreement with respect to data was not found: M82 configuration does not disintegrate enough injected particles!



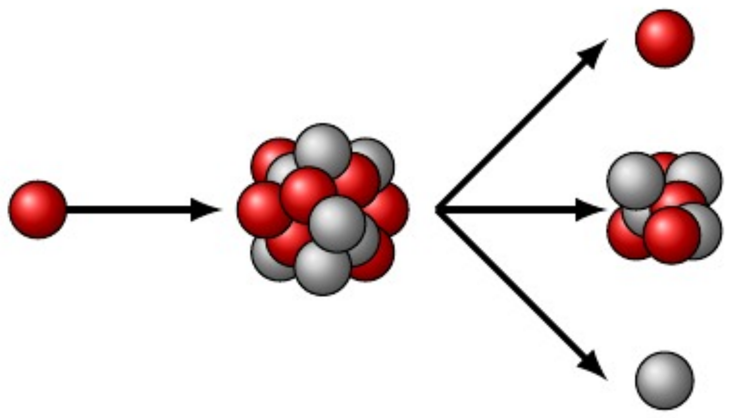


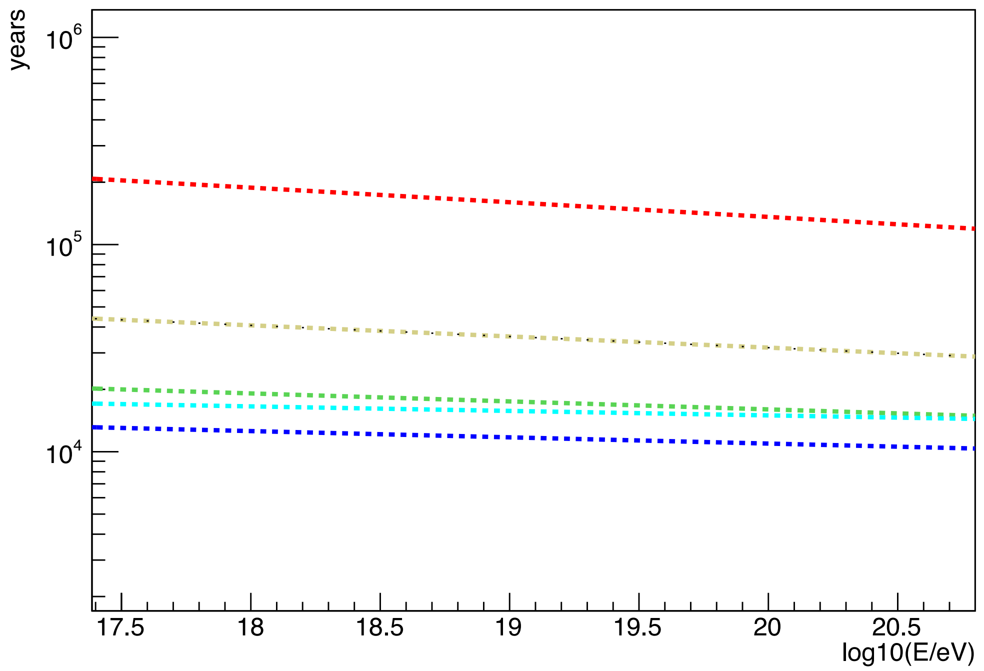
Including hadronic interactions

- The p-p and p-A cross section σ are used to calculate the interaction time
- If a hadronic interaction happens, then the interacting nucleus A is disintegrated in a nucleus $A_{\text{frag}} < A$, producing $A - A_{\text{frag}}$ nucleons.
- For each interaction a certain number of charged pions $N_{\pi^\pm}$ are produced according to a flat distribution in rapidity.



σ, A_{frag} and $N_{\pi^\pm}$ are obtained using Sibyll 2.3d.





F. Riehn et al, Phys. Rev. D 102, 063002 (2020),